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Southeastern Forest Experiment Station
Asheville, North Carolina

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Multiresource Inventories--A New Concept for Forest Survey

by

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INTRODUCTION

The way a nation manages and uses its natural resources largely determines its economic strength, the integrity and quality of its environment, and the satisfaction and well-being of its people. Finite resources such as oil and minerals are being exhausted, forcing us to rely on renewable resources—those that can be reproduced and perpetuated. America's forest and range resources are good examples.

As America increases its dependence upon forest and range resources, there is a growing need to understand the complex interactions among their many uses. At issue is the optimum allocation of these resources among the various uses. The public and its planners and decision-makers must have adequate, up-to-date information if a rational course of action is to be charted. This Paper describes an approach and system for obtaining the information.

NEED FOR BETTER RESOURCE INFORMATION

The Nation has adopted a policy of multiple use of its forest and rangelands. Strong public pressures are being applied by special interest groups to favor one use over another. There is an acute need for better resource information to help resolve these complex resource issues.

Multiple-use management requires a balance of multiresource information. While conventional forest inventories have provided a wealth of information on timber, they have not been designed to inventory the forests from the standpoint of multiple use. From this standpoint, the species composition, quantity, and spatial arrangement of the lesser vegetation become as important as the trees. Whereas rough, rotten, hollow, or dead trees might have little or no value for timber, these same trees are valuable for wildlife habitat.

The idea put forth in this Paper is to build multiresource inventories on the foundations already established for timber. The proposal is to expand the scope of conventional timber inventories to include the species composition, quality, and spatial arrangement of total biomass, and nontimber attributes of each significant plant community. The primary objective of these inventories would be to monitor the successional stages of each significant plant community in both

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the presence and absence of man's intervention. Because of the magnitude of the inventory task, we envision continued reliance upon sampling as opposed to mapping. Nevertheless, ecological information obtained from the inventories would contribute greatly to in-place use and management of the resources.

WHO WILL PROVIDE THE INFORMATION?

Within the research arm of the Forest Service, Renewable Resources Evaluation (RRE) is a logical candidate for assuming the added inventory responsibilities. RRE, formerly known as Forest Survey, dates from about 1930 (Doig 1976). Chartered by the McSweeney-McNary Forest Research Act of 1928, Forest Survey conducted the conventional forest inventories referred to earlier. Passage of the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 broadened the scope of Forest Survey activities. RRE was directly involved in the initial implementation of RPA.

Organized into regional Work Units, RRE possesses a wealth of experience in both inventory and resource analysis. In response to the RPA requirements, the RRE Work Unit in the Southeast proposed procedures for expanding its Forest Survey activity into a multiresource inventory. The Forest Service authorized RRE to test these procedures in a pilot study during the fifth inventory of South Carolina.

PURPOSE OF THIS PAPER

The purpose of this Paper is threefold: (1) to summarize the background of RRE's forest inventory activity in the Southeast, (2) to document an approach to multiresource inventories, and (3) to report on the status of the South Carolina Pilot Study.

BACKGROUND

The McSweeney-McNary Forest Research Act of 1928 recognized the importance of timber resource inventories. Section 9 of this Act authorized and directed the Secretary of Agriculture to make and keep current ". . . a comprehensive survey of the present and prospective requirements for timber and other forest products in the United States and its territories and possessions, and of timber supplies including a determination of ways and means to balance the timber budget of the United States." In response to this Act, the Forest Service organized the Forest Survey.

HISTORY OF FOREST SURVEY IN SOUTHEAST

In the Southeast, Forest Survey began statewide forest inventories in Florida and Georgia about 1933 (Knight 1972). The inventory method was patterned after procedures used in Sweden and Finland. Crews followed compass lines spaced 10 miles apart and sampled 1/4-acre plots at intervals of 660 feet along these lines. Within the forest, crews classified each plot as to forest type and stand size, tallied the trees by species and size to determine volume, and bored selected sample trees to determine diameter growth rates. A field canvass of primary wood-using plants provided information for estimating timber cut.

Data collection in this initial inventory of the Southeast extended over 7 years and was completed in Virginia in 1940. After completion of the initial inventory of the Region, Forest Survey stopped plot sampling during World War II but continued to compile, analyze, and report information. Since computers were not yet available, most of the computations were performed with desk calculators. Nevertheless, these efforts provided planners and decisionmakers with their first systematic measure of the timber resource for an entire Region.

In 1946, Forest Survey began its second inventory of the Southeast in South Carolina. This inventory was completed in Virginia in 1957. Methods differed significantly from those used the first time around. Aerial photographs, then available for most areas, were used to interpret land use and to select and locate ground sample plots. Crews located and measured 1/5-acre sample plots randomly selected and systematically distributed by grids printed on aerial photographs. In addition to classifying areas and counting and boring trees, crews tallied stumps of recently cut trees to estimate timber removals. Again, canvasses of wood-using plants provided for breakdowns of the removals by product. Special studies provided utilization factors needed to relate the removal estimates to product output.

A primary objective of the second inventory was to determine trends in the timber resource. For the first time, crews marked and described the locations of the sample plots so they could be remeasured. Experience had shown that permanent sample plots were needed to improve estimates of timber growth, mortality, and removals and to monitor changes in the resources.

By the midfifties, Forest Survey information had been accumulated for most of the country. With this information, the Forest Service made the most extensive review of the Nation's timber resources ever undertaken. The Forest Service published the results of this review in a 713-page report, "Timber Resources for America's Future" (USDA FS 1958).

Without any delay, Forest Survey began its third inventory of the Southeast in 1957; the job was completed in 1966. The basic theory of point sampling had advanced to accepted application. Instead of tallying all trees on a fixed-area sample plot, an angle-gage was used to select sample trees based on tree diameter and distance from plot center (Grosenbaugh 1952). Crews tried two modified versions of this new sampling technique during the third inventory cycle. In South Carolina, Florida, Georgia, and the Coastal Plain of North Carolina, crews superimposed a single basal area (BA-10) plot over each of the old 1/5-acre plots. In all subsequent inventory work, crews installed a 10-point cluster of BA-37.5 plots at each of the locations. The latter plot design significantly reduced the number of sample locations required to achieve the desired minimum accuracy.

In the third inventory, emphasis was placed on obtaining more reliable measures of the components of change—timber growth, mortality, and removal. While the remeasurement opportunity afforded by permanent plots was under study, crews continued to bore trees for diameter growth rates and to make stump counts for estimating removals. By 1959, most of the technical problems had been worked out and thereafter growth, mortality, and removal were estimated largely from remeasurement data.

Other significant sampling procedures introduced toward the end of the third inventory cycle included (1) a proportionate distribution of the sample plots across all land uses to enhance the measure of land-use change, and (2) a tree-volume subsample to improve volume prediction equations. The computer was fast replacing desk calculators and tabulators in processing the data.

The Forest Service undertook another comprehensive review of the Nation's timber resources in the early sixties. Again, Forest Survey data provided the basis for the appraisal. This appraisal focused on trends and projections of prospective timber supplies, "Timber Trends in the United States" (USDA FS 1965).

The fourth inventory of the Southeast was begun in 1966 and completed in 1977. During this fourth cycle, Forest Survey completed its shift to the 10-point cluster of BA-37.5 plots to determine inventory volume. Estimates of timber growth, mortality, and removals were based entirely on remeasurement data. Forest Survey continued its tree-volume subsample, timber utilization studies, and timber product output studies. The latter studies are conducted through cooperative efforts with the individual States. In 1968, starting with the fourth inventory of Florida, Forest Survey intensified its land-use sample both on photos and on the ground from a grid of single points to a grid of 16-point clusters.

During the early seventies, the Forest Service made still another appraisal of the Nation's timber resources. This appraisal occurred at a time when forest policies and forestry practices were being seriously questioned and reexamined. The appraisal focused on the condition of the forests and the identification of opportunities available for increasing prospective timber supplies, "The Outlook for Timber in the United States" (USDA FS 1973).

Throughout the first four inventory cycles, demand for Forest Survey information on the Southeast increased. While the primary objective of Forest Survey was to provide data for the national appraisals, State and local uses of the data further supported the need for the program. Because of frequent requests for data, Forest Survey established a comprehensive data bank and information retrieval system in 1970. Called Forest Information Retrieval (FIR), the system provides for rapid compilation of forest and timber statistics on a custom basis and at a nominal cost (McClure 1972). With FIR, information can be compiled in three ways: (1) whole counties grouped together, (2) circular areas around a specified point, or (3) irregular boundaries within a closed traverse of short-line segments.

Increased State and local use of the information also generated strong pressure to shorten the inventory cycles, intensify the sampling, and collect additional information. A National Handbook establishes the goals in each of these areas by specifying information required for national appraisals, minimum accuracy standards, and the periodicity of the inventories. Funding and manpower limitations have at times extended the inventory cycles beyond the established goals. At other times, cooperative assistance has enabled Forest Survey to finish early.

TRADITIONAL TIMBER INVENTORIES

All the inventories mentioned thus far focused primarily on timber. While they provided the official estimates of total forest acreage, detailed classifications and measurements were generally confined to lands classified as commercial timberland. Traditional area classifications included forest type, site class, stand size and age, stocking condition, and ownership. In the more recent inventories, additional area classifications have included stand origin, stand history, physiographic class, slope, aspect, and treatment opportunity.

The inventories have provided tree counts and their associated volumes by species, diameter, and quality along with their growth, mortality, and removal rates. Together, the area classifications, tree counts, and volume estimates have adequately described the makeup of the forest resources from the standpoint of timber. The inventories have largely ignored lesser vegetation and any attributes unlikely to influence timber production.

RESOURCES PLANNING ACT— A TURNING POINT

A growing awareness of the complex interactions among the many forest uses together with a recognition of acute problems in the budgeting process led Congress to pass the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974. RPA directed the Secretary of Agriculture to prepare a Renewable Resource Assessment not later than December 31, 1975, to be updated during 1979, and each 10th year thereafter. RPA stated the Assessment ". . . shall include but not be limited to:

(1) An analysis of present and anticipated uses, demand for, and supply of the renewable resources of forest, range, and other associated lands with consideration of the international resource situation, and an emphasis of pertinent supply and demand and price relationship trends;

(2) An inventory, based on information developed by the Forest Service and other Federal agencies, of present and potential renewable resources, and an evaluation of opportunities for improving their yield of tangible and intangible goods and services . . ."

RPA superseded the McSweeney-McNary Forest Research Act of 1928 and has been described as a bold new experiment in resolving resource issues. In addition to its requirement for periodic Assessments, the Act directed the Secretary of Agriculture to develop a long-range Program for the Nation's renewable resources that will assure an adequate supply of forest and range resources in the future while maintaining the integrity and quality of the environment. The Act called for the Program to be prepared by December 31, 1975, subject to revision in 1980 and every 5 years thereafter.

Because of the short time available, the 1975 Assessment and Program were prepared from existing data obtained from the Forest Service and other agencies. In developing the Program, the Forest Service grouped all its activities into six resource systems: (1) outdoor recreation and wilderness, (2) wildlife and fish habitat, (3) range, (4) timber, (5) land and water, and (6) human and community development. After analyzing data available for each resource, the Forest Service developed several broad alternative goals for each system. The goals ranged from less than the current trend in activities to well above current program levels.

For each goal, the agency developed targets of measurable outputs of goods and services such as acres of wilderness, animal-unit-months of grazing, or board feet of timber. Each target was translated into specific activities needed to meet that target, by relating inputs of dollars and materials to outputs of resources, benefits, or services. This procedure created more than 5,000 possible combinations of activities from which to select a unified program. From these possible combinations, the agency developed eight alternative programs for public review. These eight alternative programs offered a variety of reasonable options, ranging from a reduction in present levels of operation to intensive management of virtually all activities. After subjecting the eight alternatives to extensive public review, the Recommended Program was approved by the Secretary of Agriculture and transmitted to Congress by the President in accordance with RPA.

The final chapter in the first Assessment addressed the subject of scientific information and data needs. The Assessment acknowledged that "inventories of forest, range and inland water resources are basic to almost any decision concerning the management or use of these resources." The Assessment further acknowledged the contributions from Forest Survey and pointed out needs to accelerate the inventory cycles, intensify the samples to provide more precise local data, and expand the Forest Survey to include forest and range resources other than timber. The Recommended Program called for the Forest Service to expand its research activities in several areas, including "resource inventory and evaluation." The agency changed the name of Forest Survey to Renewable Resources Evaluation (RRE) and began techniques research on the problems associated with multiresource inventories.

MULTIRESOURCE PILOT STUDY IN SOUTH CAROLINA

The RRE Work Unit in the Southeast was authorized to test its proposed multiresource inventory procedures during the fifth forest inventory of South Carolina. South Carolina has a representative range of the forest conditions found in the Region. The State contains a portion of the Southern Appalachian Mountains, a large area of rolling Piedmont conditions laced with narrow flood plains, an extensive belt of sandhills, and a broad expanse of flat coastal plain interspersed with swamps and broad flood plains. For inventory purposes, the State is divided into three Survey Units: (1) Southern Coastal Plain, (2) Northern Coastal Plain, and (3) Piedmont. The mountains occur in the Piedmont Unit and the sandhills occur in both Coastal Plain Units.

Fieldwork began in South Carolina in April 1977 and was completed in September 1978. The new data for the Piedmont became available in late 1977, and some of the basic forest statistics have been published (Snyder 1978). Currently, RRE is subjecting the data to validation analysis from the standpoints of both timber and nontimber interests. Plans call for a comprehensive and balanced analysis of all the data at the State level.

APPROACH

The approach taken by Renewable Resources Evaluation was to expand the timber-oriented inventory into a broader, multiresource inventory by making maximum use of established inventory methods and providing an orderly transition. The first major task was to explore possibilities and select an appropriate course of action. The plan that evolved was described in a prospectus, "Evaluating Renewable Forest and Rangeland Resources in the Southeast."

Experience with timber inventories provided us with a good understanding of the problems associated with resource evaluations. There are certain similarities in the ways different renewable resources can be inventoried. Hence, computer and data management systems, maps, aerial photographs, coding systems, and field-data-collection operations designed for timber inventories could likely be used with minor modifications in dealing with the nontimber resources. It was obvious, however, that certain aspects of the multiresource inventory would require highly specialized methodology and techniques.

DEFINING RENEWABLE RESOURCES

One important planning element was a definition and understanding of what should be included as Renewable Resources. Preliminary work by the National RPA assessment team produced a working definition and listing of resources to be included:

Renewable resources.—Those resources whose use can be maintained indefinitely if the use rate does not exceed the ability to renew the supply. Renewable resources for which the Forest Service has some responsibilities include:

1. Timber
2. Range
3. Wildlife
4. Fisheries
5. Water
6. Recreation
7. Wilderness
8. Land

Forest and rangeland are two major land-use classes which were specifically identified by the Resources Planning Act. Therefore, they were of particular importance to Forest Service resource evaluations and needed to be clearly defined. Again, preliminary work done on the Assessment produced useful definitions for these key classes of land use.[1]

Forest land.—Land at least 10 percent occupied by forest trees of any size or formerly having had such tree cover and not currently developed for nonforest use.

Rangeland.—Land on which the native vegetation (climax or natural potential) is predominantly grasses, grasslike plants, forbs, or shrubs suitable for grazing or browsing, and present in sufficient quantity to justify grazing or browsing use. Rangelands include grasslands, savannas, shrublands, most deserts, tundra, alpine communities, coastal marshes, and wet meadows.

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[1] On July 12, 1976, the Forest Service and Soil Conservation Service jointly agreed on a common set of definitions which differ slightly from those presented here.

The Forest Service elected to place renewable resources into six major resource systems, which provided additional structure for a resource evaluation. For inventory purposes, the definition of a resource system and the six major resource systems were:[2]

Resource system.—A major Forest Service endeavor, mission-oriented, which fulfills statutory or executive requirements and indicates the collection of activities from the various operating programs required to accomplish the agency mission.

1. Outdoor Recreation and Wilderness
2. Wildlife and Fish Habitat
3. Rangeland Grazing
4. Timber Resource
5. Land and Water
6. Human and Community Development

In addition to the six major resource systems, the Forest Service identified eight major uses of forest and rangeland:

1. Wildlife
2. Grazing
3. Outdoor Recreation
4. Timber
5. Water
6. Wilderness
7. Other Uses (parks, scenic rivers, historic sites, etc.)
8. Minerals

Within the broad areas covered by the six major resource systems and eight major-use categories, there are numerous individual renewable resource subjects which relate in one way or another to the general concepts of renewable forest and rangeland resources. The question was: Which subjects would be appropriate for RRE to deal with and how could this be done?

FOUR WAYS TO GATHER ADDITIONAL INFORMATION

The approach taken by RRE was based on several general concepts. The total land and water area of each county and State can be separated into land-use classes, each with unique and meaningful characteristics. Each class can be further stratified into subclasses that offer relative homogeneous resource-use opportunities. For example, forest lands can be stratified by forest type, stocking, ownership, site class, stand age, etc.; marshlands can likewise be stratified by characteristics such as vegetation type, fresh or salt water, size of marsh, coastal or inland, etc. Water can be separated into streams and lakes and further stratified by width or size.

Assignment of land-use classes offers two distinct advantages: (1) RRE's permanent sample grid points falling in each use class can be revisited, subsampled, or otherwise used as a proportionate sample of the entire land base. (2) Changes in acreage in use classes can best be measured using a permanent grid of samples in all land-use classes. The land-use classes now recognized in the five Southeastern States are:

1. Commercial Forest
2. Productive-Reserved Forest
3. Other Forest (formerly Unproductive Forest)
4. Cropland
5. Improved Pasture
6. Natural Range
7. Idle Farmland
8. Other Farmland (including farmsteads)
9. Urban and Other
10. Marsh
11. Water

Permanent grid points falling in each of the above land-use classes are further classified by using aerial photographs, direct observation from aircraft, or ground checks. Points on forest and rangeland are generally visited on the ground and numerous measurements and classifications are recorded. Points in other land-use classes are simply verified, and a minimum of data is recorded.

Four general methods appeared to be available for gathering additional resource information:

1. Taking additional measurements and observations at the existing permanent grid samples established in all land-use classes in the Southeast.

2. Other sources of information taken from maps and overlays or sample data located by geographic coordinates could be combined with inventory sample data to produce a more complete composite description of the area sampled. This type information can also be summarized by geographic area and used to supplement the analysis.

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[2] For its 1980 RPA Program, the Forest Service is using 11 resource elements instead of these 6 resource systems.

3. Special sampling schemes could be developed using some combination of remote sensing, conventional or high-altitude aerial photography, direct aerial observation, and ground sampling.

4. Available information could be obtained in essentially final form from other sources. Statistics on hunting and fishing, populations, employment, and payrolls, for example, can be obtained in this manner.

With at least four possible ways to collect or otherwise acquire additional data on renewable resources, the question became one of where to start. We decided to concentrate on the first method. The reasoning was that it would take a complete inventory cycle of 8 to 10 years to gather new data uniformly across the Southeast, and that the process should begin immediately. The other methods could be used to gather broad coverage information in a relatively short time. Another consideration was that most of the information needs already identified would require ground sampling.

CONSULTING WITH SPECIALISTS AND EXPERTS

When the RPA passed in 1974, Forest Survey had been conducting timber inventories in the Southeast for over 40 years. Because timber had been emphasized, the project team contained specialists in mensuration, timber-resource analysis, sampling, computer science, and timber utilization. The responsibilities associated with the RPA created a need for additional expertise in specialties such as wildlife, range, recreation, ecology, hydrology, and soils. In the long term, this need for additional expertise could be satisfied by adding specialists to the project staff, but an alternative short-term solution was necessary.

The need to gain expertise without adding specialists to the project was partially satisfied by selected reading and study of nontimber resources. The more important source, however, was through contacts with specialists and experts at research stations, universities, State agencies, other Federal Agencies, and throughout the Forest Service.

Help of many individuals was enlisted at a variety of seminars, meetings, and programs attended by RRE scientists. Specialists in wildlife, range, recreation, hydrology, soils, ecology, etc., were asked to provide suggestions for improving the inventory in their particular area of expertise. The same individuals were asked to review new procedures, to comment on direction, and, finally, to visit inventory crews at work in the field. Although each individual's contribution may have seemed small, the aggregate contribution of dozens of individual scientists, specialists, and experts was vital in developing an experimental multiresource inventory in South Carolina.

ADAPTING EXISTING INVENTORY METHODS

To expedite the development of a multiresource inventory, the RRE staff searched for nontimber inventory methods that were already operational. It was obvious that there would not be enough time to develop and test a completely new set of nontimber inventory methods and still meet the 1980 Assessment target dates. The search for proven methods was partially successful. The published works of MacArthur and MacArthur (1961) provided several useful concepts and techniques which were adapted into a procedure for measuring vegetative profiles. The procedure developed in Mississippi (Lentz 1974) for ranking wildlife habitat proved valuable and added to the inventory. Field procedures used by the Tennessee Valley Authority, Norris, Tennessee, were adapted for measuring and coding nontimber variables. The forest range inventory procedures developed in Louisiana (Pearson and Sternitzke 1974) were modified slightly and added to the inventory. Numerous other procedures were gleaned from the literature. And finally, a number of experimental concepts were added on a test basis to achieve a well-balanced coverage of the nontimber resources. As the South Carolina Pilot Study progressed and other specialists reviewed the fieldwork, a number of additions were made to the inventory.

THE SOUTH CAROLINA PILOT STUDY

In 1976, South Carolina was selected as one of the six pilot study areas in the United States to be highlighted in the 1980 RPA Assessment. The specific mission in South Carolina was to develop and test procedures for multiresource inventories (USDA FS 1977). RRE in the Southeast had been involved in a number of nontimber resource studies and had a general conception of the additional inventory needs. The pilot study, therefore, permitted the development and testing of a number of new procedures. There were several reasons why South Carolina was an excellent place to test new inventory methods:

1. The State Forester and the South Carolina Forestry Commission were expected to fully support this inventory.

2. The forest industry in South Carolina was diversified and its reaction would be representative of forest industries throughout the Southeast.

3. The State Extension Forester had indicated his intention of fully supporting and being involved in the new inventory.

4. Station Research Work Units within the State could provide some expert assistance needed to broaden the survey.

5. The South Carolina Wildlife and Marine Resources Department had indicated considerable interest in working with RRE in several ways.

6. South Carolina is centrally located in the Southeast and has a good representation of southeastern forest conditions.

7. South Carolina is the smallest of the five Southeastern States, and can be inventoried in a reasonably short time. Its three Survey Units offered three separate opportunities to try new procedures.

SPECIAL FEATURES OF THE PILOT STUDY

Since the sampling needs for nontimber resources and analytical methods were uncertain, procedures were developed to take full advantage of 4,230 permanent forest sample locations established during the previous inventory of South Carolina in 1966–68. Consultations with experts on soils, hydrology, range, wildlife, ecology, and outdoor recreation prior to the pilot study revealed that many data elements already being collected for timber inventories were equally useful in assessing nontimber attributes (Sternitzke and Pearson 1974). We looked particularly for such link variables, which are indicative of more than one resource condition. This approach permitted us to make additions instead of building an entirely new system. Classifications and measurements made at each sample location focused on special information needs for evaluating wildlife habitat, recreation use, range suitability, water quality, erosion hazards related to forestry practices, and the use-interaction relationships associated with the numerous forest conditions occurring throughout the State. A major goal in the new procedure was to quantify and describe all the vegetation in South Carolina's forests. The theory was that the vegetative makeup of different forest conditions reflects the basic ecological relationships vital to multiresource evaluations.

A SHOWCASE INVENTORY

Since the South Carolina multiresource inventory was brand-new, it became a showcase as soon as word about it spread. Many inquiries about procedures were received long before the sampling methods and procedures were outlined in the field guide. Due to the enthusiasm and interest in this new inventory, a number of individuals were invited to review the procedures on the ground. Representatives from other RRE projects, States, Forest Service Region 8 (R-8), Southeastern Area State and Private Forestry (SA), National Aeronautics and Space Administration, and Soil Conservation Service visited sample plots near Spartanburg, South Carolina. Discussion there centered on sampling procedures, plot layout, kinds of information being collected, and reasons for including items in the study. Our goal was to obtain critical review of our procedures while we were keeping interested specialists informed. Many suggestions and ideas evolved from the mixing of different disciplines on the demonstration plots. For example, soil experts visiting the demonstration plots showed us how slope length should be evaluated. Field procedures were later modified to apply the new concept across the entire State. This review generated a lot of support for RRE and involved specialists who would be helpful in the future.

STEERING COMMITTEE

To encourage formal communication within the Forest Service as well as to provide direction, an In-Service Steering Committee was formed. Its three members were: Leroy Jones, SA, Atlanta; Jim Sabin, National Forest System, Atlanta; and Dave Olson, Southeastern Station (SEFES), Asheville. Representation from all arms of the Forest Service provided a coordinated research effort. The Steering Committee prepared a study plan, helped arrange for external involvement, monitored progress of the inventory, assisted in analysis and evaluation, and assisted in preparation and review of the South Carolina reports.

SOUTH CAROLINA STUDY PLAN

The study plan that the Steering Committee prepared outlined the objectives of the pilot

study, provided a schedule of both In-Service and external involvement, and discussed the types of reports that would be produced. The study plan named experts and specialists from the three arms of the Forest Service who could provide guidance and technical expertise. The specialists listed were:

Forest Resource Planning:	
James Wells	SA
Recreation:	
David Scott	R-8
Nathan Byrd	SA
Kenneth Cordell	SEFES
Soils:	
John Corliss	R-8
Carol Wells	SEFES
Wildlife:	
Malcolm Edwards	R-8
Nathan Byrd	SA
Michael Lennartz	SEFES
Richard Harlow	SEFES
Robert Hooper	SEFES
William Moore	SEFES
Range:	
Robert Gashwilder	R-8
Nathan Byrd	SA
Clifford Lewis	SEFES
Hydrology:	
George Dissmeyer	SA
James Douglass	SEFES
Ecology:	
Stephen Boyce	SEFES
Botany:	
Levester Pendergrass	R-8
Andrew Robinson	SA

Specialists from R-8 and the SA (1) reviewed data being collected and made recommendations for changes, (2) field-tested the feasibility of collecting new data, and (3) analyzed and evaluated data collected. Specialists from the Southeastern Station were called upon as needed to ensure that the experimental data were being collected in a scientifically acceptable manner. They were also given opportunities to assist in the analysis and reporting.

INFORM AND INVOLVE

Information about the South Carolina Pilot Study was disseminated to individuals and groups in three ways: (1) seminars at universities, (2) field demonstration plots, and (3) work meetings for all experts and specialists identified in the study plan. The purpose of a work meeting was to review progress, explore possibilities of analyzing data, and seek ways to improve future inventories.

Regardless of the source, each suggestion or new idea was considered. If it fell within the scope of the South Carolina Pilot Study and was suited to our type of sampling, it was incorporated into the study.

SEMINARS

Seminars were conducted at Clemson University, Virginia Polytechnic Institute and State University (VIP & SU), University of Georgia, Duke University, and University of Florida. We hoped to find professors and graduate students who could devote full time to items of highest priority. These high-priority items included wildlife habitat ranking, forest range, soil erodibility characteristics, diversity, fisheries, and biomass.

Both Clemson University and VPI & SU showed great interest in the inventory, and cooperative research agreements were made to meet several pressing needs. The main objectives in the cooperative agreements with Clemson University were: (1) To assess the potential of the South Carolina multiresource system to supply data useful in recreation planning. (2) To provide a method and related criteria for the inventorying of nondeveloped, rural recreation resources through the RRE field crews. Initially, the agreement was set up to run 1 year, but the preliminary results for the Piedmont Unit looked so promising that a 1-year extension was granted to Clemson University.

The cooperative agreement signed with VPI & SU had two major purposes:

1. To review the sampling techniques and habitat criteria being developed for wildlife habitat analysis.
2. To review the habitat evaluation procedure used for ranking wildlife habitat into suitability classes according to potential value.

The agreement with VPI & SU will run for approximately 2½ years.

JOINT RESEARCH PROJECTS

Sometimes it is highly desirable for two units to join forces on a research problem. When this is done, each unit can do what it does best. Presently, RRE has made two joint research agreements with other units to work on problems related to the South Carolina Pilot Study. The first agreement, with the Southeastern Station's Endangered and Threatened Wildlife research unit at Clemson, South Carolina, has a twofold purpose: (1) to estimate the extent and distribution of red-cockaded woodpecker habitat in the South, and (2) to categorize the avian species and communities associated with forest types and successional stages. The other joint research is with the unit studying Utilization and Technical Characteristics of Southern Timber at Athens, Georgia. The objective of this joint effort is to reliably predict green and dry weights for wood and bark of 140 tree and shrub species growing in the Southeast. With this type of information RRE can express its inventories in tons as well as cubic feet.

ADDING EXPERTISE TO RRE PROJECT

There are five ways to add additional analytical expertise to the RRE Research Work Unit:

1. Recruiting and adding specialists to RRE.
2. Adding specialists to other Research Work Units and assigning them to work with RRE.
3. Developing cooperative agreements with universities.
4. Having formal arrangements with other Research Work Units, Region 8, or SA.
5. Developing expertise within RRE through additional training and education of project staff.

The last three of these methods have been utilized. Even though these steps have been taken, additional analytical expertise is still needed. If pressures were not so great for a shorter inventory cycle and a more complete and intensive sample, the solution would be obvious—reduce the field effort and strengthen all RRE analytical capabilities. This, however, would be contrary to the wishes of most interested RRE supporters. The compromise solution seems to be to keep the RRE field force strong, shorten the inventory cycle, provide adequate sampling intensity along with broad subject-matter coverage, and strengthen analytical capability to the extent possible with available resources. To accomplish this will require a carefully planned strategy and selection of highly qualified specialists.

RRE plans to strengthen its in-house analytical capabilities by recruiting immediately a qualified ecologist to coordinate the analytical work to be done in wildlife, range, ecology, botany, and use interactions. Within 5 years, RRE will: (1) select at least one individual from the RRE field force to add to the Analysis or Techniques Section, (2) add a qualified individual to the Techniques Section, (3) recruit a qualified range specialist, and (4) add additional expertise in subject areas of quantitative sciences, operations research, soils and hydrology, and botany.

NEW CONCEPTS AND TECHNIQUES

Despite efforts to use existing techniques whenever possible, we found it necessary to develop new techniques in all three areas of the inventory process—data collection, data computations, and analysis. For data collection, we designed new field forms for rapid data processing, perfected ways of measuring and recording lesser vegetation in layers, and provided a set of standard procedures for measuring limbs on standing and felled trees. Data processing concepts were developed so that the vegetative information could be stored in layers and used for wildlife habitat ranking. Search of the literature and contacts with individuals did not reveal a suitable approach to analysis. Basically, no one had tried to use the same data base to assess all the different uses, interactions, and conflicts among resources. The studies that follow highlight some of the major techniques developed and adopted.

USE INTERACTIONS

At any point in time some use interactions are compatible while others are not, and the degree of compatibility tends to change over time. We are concentrating attention on interactions among timber, wildlife, range, recreation, and soil, water, and fisheries as a group. Since different management strategies are necessary to optimize use, conflicts develop among uses. Since timber is a primary product of most managed forests in the Southeast, our analysis is designed primarily to show interactions between timber production and that of other resources.

Table 1 demonstrates this approach; it shows effects of possible timber treatments on soil and water quality. Individual rows in the table show the acreages which need silvicultural treatment during the next 10 years. These practices are needed to increase timber supply, but what are the soil and water-quality risks? It is apparent that the intensity of silvicultural practice used to take advantage of the opportunity will profoundly influence soil and water quality. For example,stand conversion could be applied on 50,000 acres. If risk class 3 and above were judged unacceptable impacts, intensive site preparation would be acceptable on 30,000 acres and unacceptable on 20,000 acres. For the unacceptable acres, some other regeneration technique with less impact than mechanical site preparation should be used. The acreage requiring special treatment is of great interest to State and National policymakers.

VEGETATIVE PROFILE STUDY

While planning the South Carolina Pilot Study, we contacted individuals in several disciplines, and they confirmed that information on the lesser vegetation is important for assessing the forest resources. Previously, only trees 1.0 d.b.h. and larger had been measured. The concept of using lesser vegetation (tree seedlings, shrubs, vines, grasses, grasslikes and forbs) to predict relative suitability for different wildlife species, or to rank range capability, was well documented. Lentz (1974) described a wildlife habitat evaluation program which depends on the recognition of lesser vegetation. MacArthur and MacArthur (1961) reported on the relationship between bird species diversity and vegetation complexity.

While RRE field crews were still inventorying Virginia, a procedure for describing lesser vegetation was introduced to determine what problems would be encountered in collecting the vegetative data in winter. Some adjustments were made before the start of the South Carolina inventory. The study conducted across the State incorporated a procedure for determining the horizontal and vertical distribution, density, diversity, and composition of the tree foliage and other vegetation associated with forested ecosystems.

Table 1.—Area of commercial forest, by treatment opportunity and soil- and water-quality risk class

Treatment opportunity	Total	Soil- and water-quality risk class[1]				
		1	2	3	4	5
	Acres					
No treatment needed	600,000	150,000	250,000	75,000	75,000	50,000
Salvage cut	10,000	4,000	2,000	4,000	—	—
Harvest	60,000	12,000	18,000	3,000	14,000	13,000
Commercial thinning	60,000	30,000	20,000	5,000	5,000	—
Precommercial thinning	50,000	20,000	15,000	7,500	7,500	—
Clearing or release	70,000	18,000	30,000	10,000	11,000	1,000
Stand conversion	50,000	10,000	20,000	7,000	7,000	6,000
Artificial regeneration	100,000	40,000	20,000	10,000	20,000	10,000
Total	1,000,000	284,000	375,000	121,500	139,500	80,000

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[1] Soil- and water-quality risk definitions.

1. During the recovery period of the activity, the water-quality impact should be slight (suspended sediment less than 100 milligrams per liter) and soil erosion less than the rate of new soil development.
2. Water quality during the recovery period of the activity can be impaired (suspended sediment greater than 100 milligrams per liter), but soil erosion should not exceed the rate of new soil development.
3. Water-quality impact can be high and soil erosion can exceed the rate of new soil development during the recovery period of the silvicultural activity.
4. Water-quality impact can be serious and soil erosion can exceed the rate of new soil development for 5 to 20 years after treatment.
5. Water-quality impact can be very serious and soil erosion can exceed the rate of new soil development for more than 20 years after treatment.

A Common Link

The species composition, level of stocking, and structural features of the stand directly influence the benefits derived from forests. The vegetative makeup of forests and ranges can be viewed as the common link for study of uses and use interactions. To illustrate, we know that herbage and browse near the ground offer both grazing and browsing opportunities to animals. By determining the kinds and amounts of herbage and browse across extensive areas of forest land, we can quantify acres available for wildlife use and determine if this use is compatible with timber production.

Building Upon Existing Timber Inventory

For years, RRE has collected information on trees 1.0 inch d.b.h. or larger, from a 10-point cluster sample. In South Carolina, we measured lesser vegetation at points 1, 2, and 3 of each 10-point cluster. At each of these three sample points, all vegetative layers are examined on a plot with a 35-foot radius. Number of vegetative layers, species composition, and relative amounts are tallied. For each naturally occurring layer, a stocking percentage based on a space occupancy is determined. To estimate space occupancy, each vegetative layer is mentally divided into individual cubic feet of space, and the proportion of these cubic feet which contain vegetation is estimated.

The tally of live trees made on all 10 points is used to calculate the space that is occupied by tree crowns. The tree classifications that are used to calculate crown volume are d.b.h., crown ratio (percentage of total height containing green live foliage), tree height, crown class (a measure of the position of the crown in the stand), and tree stocking. During data processing, the tally of trees 1.0 inch d.b.h. and larger from the 10-point cluster sample is combined with the tally of lesser vegetation to produce a vegetative profile. The profile in figure 1 depicts the vertical and horizontal structure and illustrates how broad species classes occupy the horizontal and vertical space within the sample acre.

One-Foot Sensitivity

As a common link, the vegetative profile will be used by many different disciplines. The heights of interest are quite variable (Lentz 1974), and we could not anticipate all possible demands. We therefore decided to produce profiles in which values are estimated at 1-foot intervals from the ground to the tops of tree crowns. By combining values for these individual 1-foot layers on a computer, we should be able to provide all the information most users will want.

Broad Species Classes

Field data for vegetative profiles can be collected by individuals with relatively little training in identification of shrub, vine, and grass species. After each vegetative layer is identified, the broad classes of vegetation within the layer are recorded. The broad classes of vegetation recognized are yellow pines, other softwoods, hardwoods, tropicals, shrubs, vines, grasses and grasslikes, and forbs and others (mosses, lichens, etc.). Within each broad class, there is a detailed list of species. Each species list includes a category called "other." A shrub species that cannot be identified is simply recorded as "other shrub species." This approach allows the cruiser to record the proper broad-species-class code and to account for the space occupied by every species he can recognize.

Potential Values of Vegetative Profiles

Results from the vegetative profile study will open up new avenues in resource evaluation. Some potential uses are:

1. To show distribution of plant species.
2. To show the frequencies of occurrence of understory plants.
3. To determine general availability of herbage and browse.
4. To estimate live understory and overstory fuel for predicting fire behavior.
5. To make inferences about water infiltration, surface runoff, water quantity, and water quality.
6. To serve as a base for estimating weight of lesser vegetation.
7. To monitor plant species diversity, distribution, and composition over time.

EVALUATION-SUBJECT APPROACH TO ANALYSIS

There are no standard guidelines to follow in the analysis of multiresource data. One approach is to group the various data elements into subsets pertinent to a particular evaluation subject. Over the years, RRE's involvement in limited studies of deer browse, hydrology, and red-cockaded

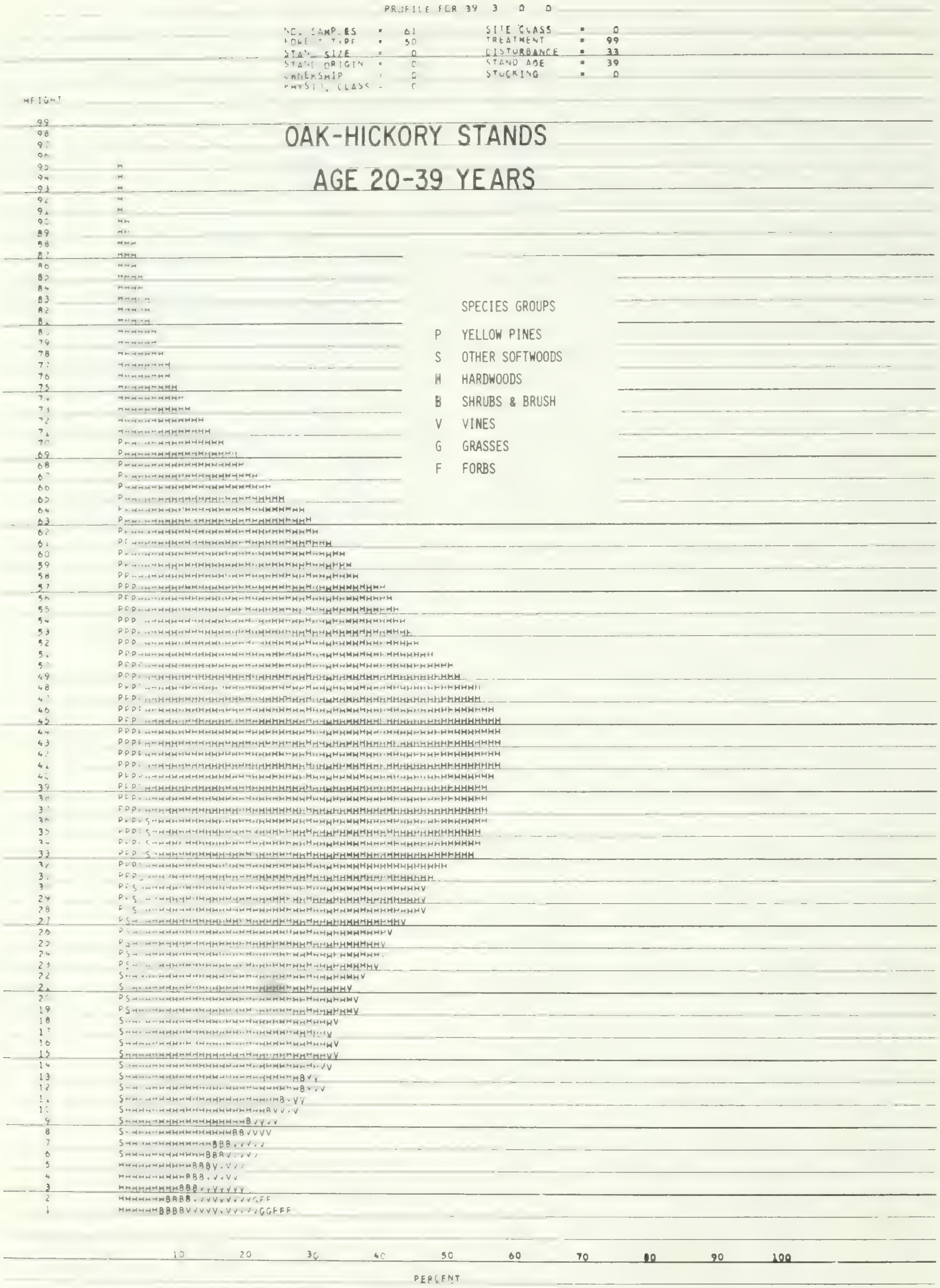

Figure 1.—Horizontal and vertical structure of broad classes of plants for oak-hickory stands, 20 to 39 years, Piedmont, South Carolina, 1977.

woodpecker habitat has provided some experience with the evaluation-subject approach. Experience gained from our studies and information from elsewhere indicate that many items tallied to evaluate timber are equally useful for evaluating other forest benefits.

We first identify those data elements having common value to all the evaluation subjects. These elements, which we call link variables, include items such as sample location, forest type, stand age, stand size, stand origin, site descriptions, and ownership class. Next, we add the more specific data elements to their appropriate evaluation subject. Here, a series of summary cards has proven helpful. Each summary card contains the basic link variables plus those data elements pertinent to the particular evaluation subject. These summary cards are used to develop frequencies, distribution rates, relationships, and correlations among the various resources and evaluation subjects.

BIOMASS INVENTORY CONCEPT

For years, RRE in the Southeast has collected biomass data from standing and felled trees for producing volume prediction equations. Quite recently, RRE modified its measurement procedure to include all the components in a tree, except the foliage and small twigs. Since additional data are being collected on lesser vegetation and foliage and twigs of larger trees, we can predict total biomass for different forest conditions. We will do additional subsampling to establish weight estimates. Total biomass as defined by RRE will not include roots.

Traditional State and regional inventories have usually been designed to provide volume estimates of wood from a 1-foot stump to a 4.0-inch-diameter outside bark (o.b.) for trees 5.0 inches d.b.h. and larger. This standard was established in 1963. During the same year, a comprehensive standing- and felled-tree volume study was incorporated into the inventory. The measurement procedure was designed to identify the stump and saw log portion, upper stem and top of main stem and forks, and all usable limbs. The only components not measured were minor limbs (limbs not suitable for pulpwood) and tips of usable limbs. This method of measuring trees provided the necessary data for predicting the standard merchantable volume.

Renewed interest in use of wood for energy and trends toward whole-tree use created a need for measures of the volume in trees 1.0 to 4.9 inches d.b.h., and in all limbs of trees 5.0 d.b.h. and larger. In 1975, measurement procedures were modified to include saplings and all limbs. The details for measuring standing trees are provided in another publication (Cost 1978b).

Since all components of trees 1.0 inch d.b.h. and larger are being measured, total-tree volume can be estimated. Cubic volume in the stump, main stem, forks, and limbs of merchantable trees can be displayed. Volume in saplings can either be included or excluded. Cost (1978a) pointed out that 30 percent of the total hardwood volume in the mountains of North Carolina was in saplings and in stumps, tops, and limbs of trees 5.0 inches d.b.h. and larger.

From cubic volume, weight can be estimated. Steps have already been taken to assemble conversion rates by species. Once this is accomplished, RRE can report timber statistics in both weight and volume.

The data being collected on vegetative profiles will provide estimates of the quantity and distribution of lesser vegetation in the understory and of tree foliage and small twigs in the midstory and overstory. If it is decided that total biomass is the main objective, we could develop weight estimates of the lesser vegetation and tree foliage by subsampling a variety of forest conditions. At each subsample location, the vegetation within a known space could be clipped and weighed. Weight conversions could be developed and applied to the entire population for biomass estimates.

INFORMATION MANAGEMENT

The timber and nontimber data collected in South Carolina can be assembled and presented in many different ways for a wide array of users. Many types of tables and charts can be generated and presented in RRE reports. In addition, by screening the data base, estimates of acreage meeting certain requirements can be generated on request.

In 1970, RRE Project Researchers at the Southeastern Forest Experiment Station made a breakthrough in both the storage of data and the retrieval of information. The result was a Forest Information Retrieval (FIR) system which provides information on a customized basis. The breakthrough in mass storage and retrieval permitted us to screen and interrogate our active data base as needed. The FIR system is a specialized

set of advanced computer programs that searches RRE data tapes and compiles customized forest resource information. With the system, requests that previously required weeks or months to compile can now be processed in a fraction of the previous time and at a reasonable cost. The system is currently geared to provide up to 44 tables of forest resource information, all clearly labeled for the analysis of any geographic area in the Southeast. The user of the system can have the information compiled in three ways: (1) whole counties grouped together, (2) circular areas around a specified point, or (3) irregular boundaries within a closed traverse of short line segments. In addition to the FIR System, we routinely present resource data in tables for States and for Survey Units (major subdivisions of States). A Unit report contains mainly statistical tables and is meant to rapidly convey basic findings. Tables in Unit reports provide data by county. The State report contains the 26 standard tables and meets all other requirements of the RRE Handbook. It is released within 1 year after fieldwork is completed. This report includes a thorough analysis of the timber situation for an entire State.

The presumption in the standard-table approach is that most significant combinations of data can be compiled in a predetermined form that will satisfy both current and future needs. This approach has not always proved adequate in answering new questions. By storing the basic data in a highly accessible form, a screening process can be used as needed to answer specific questions or to produce a chart. Figure 2 is one example of a screening which depicts the occurrence of loblolly pine on rolling upland sites in the Southeast.

The multiresource inventory will obviously generate numerous records and a tremendous amount of data dealing with many resource uses. To disseminate the wealth of new information, we will expand our FIR system, analysis, and reporting to accommodate the full range of forest values and uses.

WILDLIFE HABITAT RANKING METHODS

Earlier work by Lentz (1974) showed that plot data from broad-scale inventories can be used to rank habitat suitability for certain animals. Since a number of wildlife-related attributes were observed and measured in the South Carolina inventory, we decided to develop a screening process which would rank each plot in terms of its habitat suitability. A review of the literature revealed that habitat criteria were available for game animals, but generally lacking for nongame birds and animals. Several wildlife experts were asked to provide habitat criteria for as many different birds and animals as possible. From their responses and from available literature, we assembled enough detailed data to develop screening criteria for 12 animal species or species groups.

1. Gray squirrel
2. Grouse
3. Bobwhite quail
4. Turkey
5. Pileated woodpecker
6. White-tail deer
7. Red-cockaded woodpecker
8. Beaver
9. Cottontail rabbit
10. Small mammal group
11. Raccoon
12. Wood duck

We decided to use two types of screening because some birds and animals are highly specialized in their ecological preferences. The two methods were:

Ranking method.—This method is used for all animals that do not have specialized needs. For each wildlife species, a set of habitat variables are described. Each variable is graduated from good to poor and assigned a numerical value. The habitat of each forest condition sampled is ranked either good, fair, or poor for a particular wildlife species, based on the total accumulated points from its habitat variables. The ranking criteria for gray squirrel are presented as an example (fig. 3).

Discrete method.—This method is used to determine habitat suitability for beaver and red-cockaded woodpeckers. Only good, fair, and no habitat classes are considered for beaver. For the red-cockaded woodpecker, a remnant-tree class was included with the good, fair, and no habitat classes. To qualify as good, every attribute of good habitat must be present. If any attribute is missing, the next lower class is considered, and so on. The screening of habitat suitability is very dependent on structural features of the stand. For screening, five distinct vegetative layers were recognized:

1. Ground layer	0 to 1 foot
2. Shrub layer	1 to 5 feet

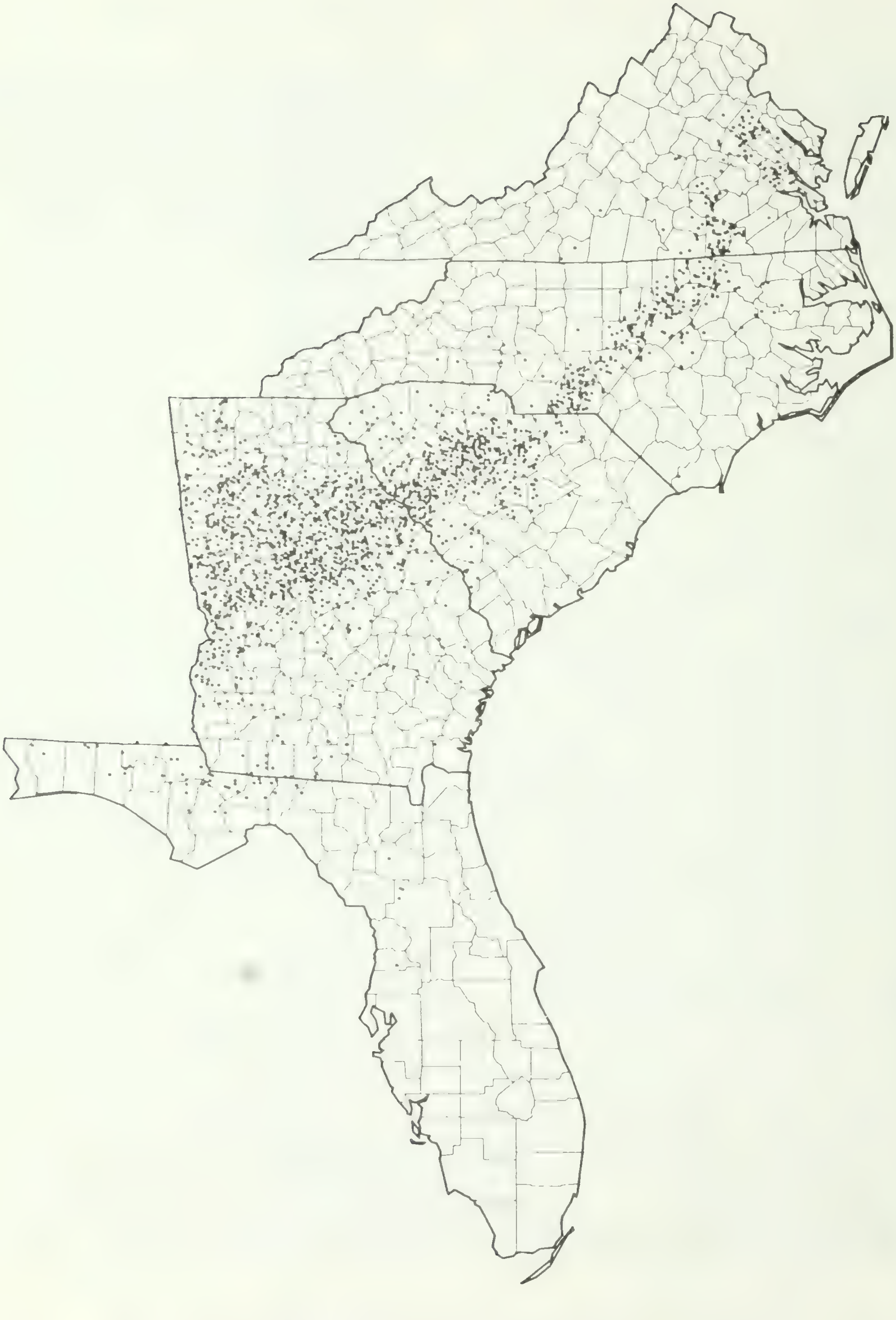

Figure 2.—RRE sample plots assigned loblolly pine type on rolling upland sites in the Southeast.

GRAY SQUIRREL HABITAT CRITERIA

Habitat Variable	Point Value
1. Forest type and stand age—	
a. bottomland hardwood types 41+ years; other forest types 61+ years	3
b. bottomland hardwood types 25 to 40 years; other forest types 41 to 60 years	2
c. bottomland hardwood types 16 to 24 years; other forest types 21 to 40 years	1
2. Vegetative stocking of desirable species in the midstory by 1-foot strata—	
a. 26 percent or more	3
b. 11 to 25 percent	2
c. 1 to 10 percent	1
3. Vegetative stocking of total vegetation in the overstory by 1-foot strata—	
a. 76 percent or more	3
b. 51 to 75 percent	2
c. 26 to 50 percent	1
4. Vegetative stocking of hardwoods in the overstory by 1-foot strata—	
a. 81 percent or more	3
b. 51 to 80 percent	2
c. 21 to 50 percent	1

Habitat Rank Determination

Habitat Rank	Code	Total Accumulated Points
Good	3	9 to 12
Fair	2	5 to 8
Poor	1	1 to 4
No habitat	0	0

Figure 3.—Habitat criteria for gray squirrel.

3. Understory	5 to 15 feet
4. Midstory	15 to 30 feet
5. Overstory	30+ feet

The level of stocking within a vegetative layer is one of the key criteria for evaluating habitat by the ranking method. Levels of stocking within a layer were analyzed in two ways:

1. Stocking by 1-foot strata
   Each 1-foot zone within a designated layer is examined for a specified level of stocking. Either stocking of all vegetation or that of desirable species can be analyzed.
2. Stocking percentage within a layer
   This stocking concept pertains to the quantity of vegetation that occupies the entire layer.

TIMBER MANAGEMENT AND TREATMENT

During the fourth inventory cycle, started in 1966 and completed in 1977, a number of improvements were made to provide a more complete picture of the region's timber resource. We classified the forest in ways that permitted evaluation of opportunities for increasing timber supplies. Two significant changes were made to improve forest resources evaluation. These included: (1) measuring stand age to nearest year, and (2) adding several new variables to enhance the identification of treatment opportunities. A few examples of significant improvements are summarized below.

Stand History

A procedure for classifying stand history was developed and added to RRE in 1970. This new approach provided information previously lacking on levels of forestry activity and the geographic location of various forestry practices. Activities such as harvesting, thinning, highgrading, and natural disturbance were identified.

Treatment Opportunity

Treatment opportunities and the related factors limiting or influencing such opportunities have been indirectly considered by RRE for many years. In 1970, a procedure was added to specifically identify and quantify forest areas by treatment opportunity classes. Some of the classes recognized are salvage, harvest, thinning, TSI, regeneration. Results indicate the value of this information in making statewide and regional evaluation of opportunities for increasing future timber supplies. For areas covering several counties, this information provides a guide for planning and a basis for allocating program efforts.

Sampling One Condition

When fixed-area plots and single-point variable plots were used in the Southeast, procedures were developed for minimizing overlap through the shifting of plot centers. When the 10-point cluster plot was adopted in 1963, provisions were made for substituting points for those which fell outside the commercial forest, but the shifting of points to keep the effective sampling area within one forest condition was discontinued. A special plot classification in the fourth inventory of Georgia indicated that about one out of every three samples straddled two or more distinct forest conditions. When overlap or straddling is permitted across plantations and natural stands, distinct types, sites, or stand sizes, unrealistic or nonexistent conditions are portrayed.

A study in central Georgia of only those plots contained within a single condition indicated that estimates of average volume per acre did not change significantly. These findings resulted in changing procedures so that each sample plot is confined within the forest condition identified by point 1.

Stand Age

Another recent improvement in inventory techniques is the redefining of stand age. RRE field crews had difficulty in classifying stand age at sample locations. Causes for this difficulty were: (1) sample plots were allowed to straddle two or more conditions, and (2) a wide range of tree diameters at given sample locations misled field crews into assigning a mixed age.

In 1972, several steps were taken to enhance the validity of the stand-age classification: (1) even-aged management was assumed at each sample location, (2) each sample plot was confined to a single forest condition identified by point 1 of a 10-point sample cluster, (3) stand age was based on stocking of trees which could be featured together in timber management, and (4) greater emphasis was placed on making an adequate number of increment borings for determining stand age. The results of these adjustments are reflected in a report titled ''Stand-Age Profile of North Carolina's Timberland'' (Knight 1977).

Stand Characteristics

Like stand age, other stand classifications were modified or redefined in order to better describe the existing forest conditions. One useful stand classification that was modified was stand origin. It is used to identify plantations and to separate them into useful categories. Other modifications were made to the stand size and seed source classification. For years, RRE field crews recorded only one stand size, either sawtimber, poletimber, sapling and seedling, or nonstocked. Since most forest stands except pine plantations have two size classes, the stand size classification was expanded to reflect both the primary and secondary size class of the dominant and prevalent stems on the sample acre. Seed source was redefined to indicate the presence or absence of suitable seed trees by species class. The suitability of a particular species as a seed source is dependent upon its square feet of basal area on the sample acre.

Availability Factors

Physical factors prevent intensive culture on some commercial forest land. As part of the inventory, a number of key variables were measured and added to the data base for screening purposes. These key variables can be used to answer questions that have economic implications. For instance: How many acres of pine sites are suited to mechanical site preparation and planting? How many acres of forest land in need of silvicultural treatment would require relatively little road construction to make them accessible for mechanical planting? How much area and volume would be excluded if small drains and narrow stream margins were not available for commercial timber production because of environmental concerns? There are additional questions that can be answered with the variables collected in the South Carolina inventory. Some of the key variables are:

- Accessibility (Describes the degree of difficulty involved in moving men and equipment to the edge of a forest stand)
- Operability (Identifies stands which present special management problems due to water conditions or steep slope)
- Slope
- Aspect
- Physiographic class (Based on soil, terrain, soil moisture, slope, and other nonvegetative conditions)
- Shape of forest condition
- Size of forest condition

EVALUATION SUBJECTS

A multiresource inventory can be regarded as a single integrated activity during planning and data collection. In analysis and interpretation, however, the entire inventory becomes too unwieldy; a breakdown into specific subject areas is a practical necessity. This separation allows the computer systems analyst and the resource analyst to focus attention on one data subset at a time, and it permits specialists to examine the data in their areas of expertise. It can also lead to better balanced and more uniform analysis and evaluation of various resource uses. We do not imply that each evaluation subject should be given equal space or time, but rather that each subject should be separately and fully considered. Some of the possible categories for separation are listed and described below.

LAND BASE

A clear definition of the land base for renewable resources including physical extent and location is necessary for a rational inventory. The inventory should identify specific areas with various specific resource-use potentials. We define the land base to include both land and inland water falling within the recognized political boundaries of each State.

There are many advantages in having a single common land base for evaluating all the renewable forest and rangeland resources. It avoids overlaps and gaps when the resources are combined, and it reduces inventory costs by eliminating duplication of field effort. Use of a single common land base also improves measures of use interaction.

The South Carolina inventory is designed to provide a broad range of information about the land base. It provides area statistics by land-use class at the county, survey unit, and State level. Trends in land use are measured both from aerial photographs and from permanent ground samples. The periodic remeasurement of permanent samples in all land-use classes provides a complete measure of change which can be used to evaluate impacts of resource use. The following evaluation subjects are all tied directly to this common inventory land base.

TIMBER

The objective of a timber-oriented inventory is to produce area and volume statistics in a useful form for analysts, managers, planners, and decisionmakers. The familiar timber resource reports usually contain tables of statistical information by forest type, ownership, site class, stand size, etc. The new multiresource inventory will not reduce the amount of timber data being collected. Collecting timber and nontimber data simultaneously will probably significantly increase the amount of useful timber-related information.

Some new information on timber is being collected as part of the multiresource inventory. New items include stand history, which is coded in terms of treatments and disturbances since the previous inventory. The condition of the forest at each sampling point is used to determine a treatment opportunity based on a set of standards for the Southeast. The structure of the forest at each sample is completely measured to enhance the classification and description of forest stands for management purposes. Several new variables describe the physical factors limiting harvest, treatment, and management of portions of the commercial forest. These characteristics include slope, aspect, accessibility, size of condition, operability, physiographic class, and a better measure of the stocking. Other improvements and refinements in inventory techniques have been made in recent years, including items such as stand age, stand origin, and seed source.

WILDLIFE

Wildlife-related information in the new inventory is confined to measuring, classifying, and evaluating habitat. Our sampling process is well suited for estimating the amounts of forest and rangelands that have the vegetative structure, species composition, and special features required by a given species of wildlife. In contrast, our procedures are totally unsuited for estimating populations of individual wildlife species. For wildlife habitat, we measure the vegetative structure, composition, and density in the overstory, midstory, and understory to estimate the abundance and distribution of wildlife plants and the adequacy of the vegetative community to provide cover, shelter, nest sites, and foraging substrate. We also note the presence of cavities and snags, which are extremely important to certain species of wildlife. Other special features recorded include cover items such as holes, caves, dens, brush piles, and hollow logs. The presence of water is also recorded in various ways to improve the description of forest habitats.

Individual wildlife species range over areas from a few feet to many miles. Some species require specific habitat conditions, while others adapt well to a wide range of conditions. Some species migrate, while others remain in one area throughout their lives. There are also numerous variations in food requirements, sensitivity to disturbance, and living space needs. Some species spend most of their time below ground, some prefer ground level, and some favor selected vegetative layers above ground. This high degree of variation in species habitat selection makes the inventory task extremely complex.

To help organize our thinking about wildlife habitats, we have recognized five broad classes of vertebrates.

1. *Migratory Species*—Species that use a particular forest condition seasonally outside of the breeding season.

2. *Threatened and Endangered Species*—Species given special status and protection because of unsatisfactory population levels.

3. *Recluse Species*—Species that require large, remote, solitary, or secluded areas of undeveloped or isolated forest. They are sensitive to development and encroachment of civilization.

4. *Adaptable Species*—Species that do not require a single specific habitat but are highly flexible and can successfully shift from one forest condition to another. Species may thrive in diverse or mixed forest conditions.

5. *Sensitive Species*—Species that require a special combination of habitat characteristics to survive and reproduce. These species are very sensitive to habitat disturbance.

Our inventory methods are poorest for quantifying habitat of migratory species. The threatened and endangered group includes species from the other groups and is actually not a separate inventory problem. The recluse group is probably better suited to in-place mapping than to broad-scale inventory sampling. The remaining two groups are the largest and our procedures are probably suited to them. The suitability of habitat for sensitive species can be ranked by screening for certain attributes at each sample location. Adaptable wildlife species probably do best where a diversity of conditions is present over a small area.

RANGE

Before the range resource can be evaluated, the land base suitable for range must be determined. Sufficient forage for grazing of livestock is present in a wide variety of situations. In the Southeast, the land-use classes of major importance to range evaluations include forest lands, natural range, and marsh, which are classed as forest and rangeland, as well as improved pasture and cropland, which are excluded from our inventory responsibility. The inventory will determine the current area in each land-use class and also measure the rates of change and trends in area.

Within land-use classes, we are measuring the quantity, quality, and distribution of vegetation suitable for livestock forage. In addition, we are noting fencing, burning, and current utilization. Our inventory will also show that water is a limiting factor. A few plants are poisonous or noxious to livestock and can be identified as a limiting factor to range use. Other species of plants are preferred or are of special importance to livestock and can be rated accordingly.

RECREATION

Our survey crews will note evidence of recreational uses such as hunting, fishing, and camping, for which signs can be found. Other recreation-related inventory information includes the presence of various types of trails, posting of forest land, and the presence of water. General

information that may prove valuable in judging recreation potential includes slope, soil texture, land-use pattern, accessibility, and a complete description of the vegetation present at the sample location.

SOILS

A limited amount of information on soils is being collected during the inventory so that certain soil characteristics can be directly related to other resource data at ground sample locations. The soils portion of the inventory was carefully designed to prevent any duplication of effort or overlap with the soil surveys being conducted by the Soil Conservation Service. One of our primary goals is to be able to inventory environmental impacts due to management actions which disturb the site. We are tallying a rough estimate of soil texture which, combined with slope, can be used to rank areas into erosion-risk classes. Other information recorded includes soil structure, compaction, and position on slope. Together, these soils characteristics are useful in judging the relative stability of the site. The inventory also includes information on litter depth, humus depth, percentage of bare ground, and a complete description of the vegetative cover.

WATER

For inventory purposes, water is treated both as a separate land-use class and as a special characteristic of the forest. As a land-use class, water is separated into lake-like and stream-like categories. It is further classified as to size or width and as fresh or salt water. The amount, kind, and distribution of water directly influence many of the other evaluation subjects such as timber, wildlife, recreation, and range.

Water in or near a site may enhance its value for a particular use or create a management problem, depending upon the use being contemplated. The inventory therefore describes the proximity of water to the forest and rangelands being sampled. We distinguish between temporary and permanent water and estimate average depth of temporary water.

The presence of water is used to evaluate the suitability of the forest in meeting the needs of wildlife, recreation, and livestock. It is also treated as a limiting factor to timber management and harvesting operations. And it is a critical in- o the next evaluation subject—fisheries.

FISHERIES

Forest and range activities can influence the quality of fish habitat. As described in the preceding segment, the inventory measures the amount, kind, and distribution of water. This information on inland waters should help in evaluating fisheries. Other useful inventory information includes the proximity of water to various forest disturbances and the degree of erosion taking place.

BIOMASS

The estimation of total biomass as defined by the ecologists is not our goal. We do not deal with roots, insects, birds nests, or other matter of a similar nature. Thus, we can only estimate the biomass of aboveground woody fiber. We can categorize this material by species, structure, and space occupied. Despite the restrictions, our biomass totals should prove useful because they include a very high proportion of all aboveground biomass. And the data are being collected uniformly across the entire State.

Traditional timber inventories have usually been designed to estimate only the volumes of material meeting certain merchantability standards. Large quantities of lower value material have been excluded. The South Carolina inventory, therefore, will provide a more complete measure of the forest biomass.

A comprehensive standing- and felled-tree volume study was initiated in the Southeast in 1963. The results provide the basic data needed to determine volumes in sapling-size trees (trees 1.0 to 4.9 inches d.b.h.) and in stumps, tops, and limbs of trees 5.0 inches d.b.h. and larger. The lower quality trees, commonly called rough trees and rotten cull trees, can also be included in these volume summaries. Wood volume, bark volume, or a combination of wood and bark volume can be presented.

The remaining step in estimating biomass is to convert volumes into weights. A separate effort is now underway to find the best available conversion rates for the various species of trees found in the Southeast. Precise conversions of volume to weight will require additional work because of variations in wood and bark, tree size, location within the tree, and geographic location.

Data being gathered on understory vegetation include the quantity, distribution, and space occupied by various species of tree seedlings, shrubs, vines, grasses, and forbs. These data will provide a basis for estimating additional vegetative mass.

ECOLOGY

Since inventory coverage is very broad, it seems desirable to examine the data from a purely ecological standpoint. Information on the vegetative structure of all the forest lands in South Carolina offers a unique opportunity to study ecological relationships on a very broad scale. The inventory will provide a picture of the composition of overstory, midstory, understory, shrub layer, ground layer, and various combinations on a statewide basis. The inventory will also provide data on species associations, and the occurrence of trees, shrubs, vines, grasses, and forbs at various stages of succession. It will identify recently disturbed areas and the vegetative responses to those disturbances.

A new procedure for displaying and analyzing the vegetative composition and structure of individual sample areas or aggregates of many sample areas is called the vegetative profile. This technique, explained in greater detail elsewhere in this Paper, is an example of how the massive amount of detail data being collected can be combined into a single clear display of the ecological structure of forest vegetation.

BOTANY

There are many aspects of the multiresource inventory that are of special interest and value to botanists. The inventory will show how the distribution of individual plant species is associated with various site conditions and other species. Understory species such as honeysuckle, kudzu, and poison ivy are of considerable interest because of their potential to create problems. The distribution associations of many other plants are in need of validation and confirmation. Botanists are also concerned about trends in the quantity and distribution of certain plants. Information obtained from the remeasurement of permanent samples will be useful in assessing trends and will help in the selection of plant species as threatened or endangered. In some cases, a plant species may be removed from the threatened and endangered list if it can be shown that its distribution is acceptable and its population trends are stable or increasing.

USE INTERACTIONS

Since our resource base is finite, all uses interact to some degree. In resource inventories and evaluations, therefore, interactions must be considered whenever two or more resource uses are being analyzed. Not all interactions are necessarily bad or harmful. Some can be harmonious and compatible. Over long periods, however, the tendency is for use interactions to be competitive and to generate conflicts.

The evaluation subjects discussed in this section are the uses which tend to interact. The most visible interactions involve timber, wildlife, range, recreation, and a composite of soils, water, and fisheries. A given piece of forest land cannot simultaneously support two or more uses which require conflicting management actions. The role of inventory is to gather and display the information needed to select a desirable balance of forest use. Measuring and classifying the forest as a single entity establishes a common data base to which specialized information about individual resources can be added.

In theory, use interactions can be thought of as a matrix in which each use interacts with every other use, both singly and in combinations. This model is very complex and suggests many analyses that are of very little interest. Furthermore, it fails to recognize the practical and biological significance of the timber overstory in forests. In the Southeast, timber is the intended product of most managed forests. In addition, the condition of the timber overstory largely controls the biological process beneath. In our first analyses of interactions, therefore, we will focus on timber's relation to other uses. The data will be organized to show the impacts and trade-offs that might be expected if timber production is maximized. Maximizing timber production would require harvesting, regeneration, and treatment strategies that may have rather serious impacts on wildlife, range, recreation, and the quality of the environment. On the other hand, the constraining of timber in favor of increases in the other uses can be evaluated in terms of reduced forest products output at higher prices. This approach does not make any attempt to evaluate use interactions between wildlife and range or recreation and environmental factors.

INFORMATION MANAGEMENT

The multiresource inventory described here

will obviously generate numerous records and a tremendous amount of data that must be properly managed before it can be fully analyzed and evaluated. The bulk of these data is recorded on forms in the field, then transferred onto data cards and magnetic tape for processing and storage. A number of specialized processing systems are used to convert the raw field data into final data storage records. Each system is composed of several individual computer programs which perform a set of mathematical and logical transformations as the data pass through the computer. The final records are sorted and stored for later use in the RRE master data base. This data base contains the accumulated inventory data for the five Southeastern States.

The primary test of an information management system, however, is its ability to retrieve information in desirable forms. If the mass of data produced by an inventory can be retrieved rapidly in forms suitable for a variety of analysts, such as providing customized responses to many different users, it has passed the test.

The FIR system used by RRE in the Southeast is a highly advanced user-oriented system for mass data storage and retrieval. It is designed to provide rapid retrieval of inventory information on a customized basis. The methods for storing, cataloging, updating, and retrieval are all common enough. The unique aspects of the system are that it is relatively inexpensive to operate and has proved to be both flexible and dependable.

THE ROLE OF TECHNIQUES

Research on inventory techniques is a highly specialized activity that can be conducted during multiresource inventories. This research requires a unique feel for what is needed, suitable, practical, and possible, coupled with an ability to make things work.

The initial step in techniques research is to identify needs and recognize opportunities. This requires a thorough grasp of inventory objectives, an appreciation of information needs, an understanding of priorities, and considerable expertise in inventory methods. Items selected for study should have high priority, be within the scope of the inventory objectives, and be amenable to solution.

The next step is to judge the suitability of existing methods and procedures. Quite often an inventory need can be met by adapting or modifying a piece of equipment, a field-measurement procedure, or a computer program rather than developing a totally new item or procedure. An entirely new technique must be taught to field crews, as must the use of new equipment. Hence, use of an existing procedure, method, or tool often saves a lot of time and money.

Where something new is needed, its development requires innovation and the forming of new concepts. This process is like that of other research; success requires both thought and persistence. A newly conceived procedure is usually incomplete and lacking in detail. Additional development is usually required before it is ready for testing.

All new methods and procedures do not require the same degree of testing. Some are so straightforward that it is obvious to inventory specialists how well they will work and the problems that might develop. Other methods and procedures do, however, require extensive field testing and possible modification before they become part of the regular inventory.

DISPLAY OF RESULTS-EXAMPLES

Multiresource data are now available for one of the three Survey Units in South Carolina—the Piedmont. In this chapter we illustrate the kinds of information available for this Region. We emphasize that these illustrations are only a few examples. Upon completion of the inventory, we plan to make a comprehensive and balanced analysis of all the data collected.

Initial estimates of forest and nonforest areas in the Piedmont Region were developed from classification of 23,831 sample clusters systematically spaced on aerial photographs. Field crews verified the photo classifications on the ground at 1,614 of the 16-point clusters. A linear regression was fitted to the data to develop the relationship between the photo and ground classifications. This procedure provided for adjusting the initial estimates of area for change in land use since date of photography and for photo misclassifications.

The Piedmont Region of South Carolina encompasses more than 6.8 million acres of land and water. The inventory provided a breakdown of this total area into meaningful land classes (table 2). Forest occupied almost 4.6 million acres, or two-thirds of the total area. By county, percentage of total area in forest ranged from 85 percent in Fairfield County to only 42 percent in

Anderson County (table 3). Anderson, Spartanburg, and Greenville Counties each have sizable urban centers. In addition, a large part of Anderson County was inundated by Lake Hartwell, one of several major reservoirs in the State. As of 1977, less than 1 percent of the forests in the Piedmont had been withdrawn from timber use, as indicated by the productive-reserved forest classification.

Table 2.—Total area, by land classes, Piedmont of South Carolina, 1977

Land class	Acres	Percent
Commercial forest	4,528,036	66.3
Productive-reserved forest	38,746	0.6
Other forest	—	—
Total forest	4,566,782	66.9
Cropland	580,348	8.5
Improved pasture	728,065	10.7
Natural range	—	—
Idle farmland	161,337	2.4
Other farmland	94,316	1.4
Marsh	2,319	(1)
Urban and other	510,612	7.5
Water	179,261	2.6
Total nonforest	2,256,258	33.1
All classes	6,823,040	100.0

[1] Less than 0.1 percent.

Over the past 40 years, Forest Survey has monitored extensive changes in land use in this Region. Forest Survey first inventoried the Region's forests in 1936. At that time, forests occupied only 3.2 million acres or less than half of the total area; about an equal acreage was in agricultural use. Between 1944 and 1969, according to Census of Agriculture statistics, the Region experienced a reduction of more than 1.2 million acres in cropland harvested. A strong correlation between the age distribution of pine timber stands in 1977 and the timing of these reductions in cropland harvested confirms that much of this cropland reverted to pine forests. This successional reversion from cropland to pine timber accounts for today's concentration of pine timber stands in the younger age classes (table 4). Over time, hardwood species tend to develop in the understory of these pine forests and without substantial intervention by man will gradually replace the pines.

Table 3.—Counties ranked by percentage of total area in forest, Piedmont of South Carolina, 1977

County	Total area	In forest	
		Area	Percent
	........*Acres*........		
Fairfield	453,120	386,015	85.2
Union	329,600	272,386	82.6
McCormick	257,920	207,036	80.3
Chester	376,960	290,814	77.1
Newberry	415,360	315,829	76.0
Edgefield	309,760	234,637	75.7
Lancaster	325,120	235,933	72.6
Greenwood	293,120	206,286	70.4
Abbeville	325,760	220,533	67.7
Oconee	424,454	284,580	67.0
Laurens	460,800	305,701	66.3
Pickens	325,626	214,980	66.0
Saluda	288,000	187,758	65.2
Cherokee	252,800	155,752	61.6
York	446,080	269,252	60.4
Greenville	508,800	299,821	58.9
Spartanburg	532,480	271,268	50.9
Anderson	497,280	208,201	41.9
All counties	6,823,040	4,566,782	66.9

We contend that this is the kind of information needed to make assessments.

For evaluation purposes, we need to relate the timber component of the forest resource to the distribution in table 4. On the 4.5 million acres of commercial forests in the Piedmont, the solidwood content between a 1-foot stump and a 4-inch top of all live trees 5.0 inches d.b.h. and larger averaged 1,462 cubic feet per acre (table 5). The sawtimber component of this timber inventory averaged 3,750 board feet per acre (table 6). In addition, these forests contained an average of 664 saplings per acre (table 7). Together tables 5 through 7 quantify the distribution of timber by stand-age class and forest types. Where needed, these distributions can be further refined by ownership and site classes and can be developed for smaller geographic areas within the Region.

Wildlife evaluations can be based on quantities of forage in various vegetative layers or on values assigned to plots as habitat for certain species. Here we show the ranking of gray squirrel habitat suitability and a screening of potential red-cockaded woodpecker habitat.

Our plot data on gray squirrel habitat for the Survey Unit show that conditions are best for this animal in the hardwood-forest type (table 8 and fig. 4). By county, the proportion of commercial

Table 4.—Area of commercial forest land by stand-age class, by forest types, Piedmont of South Carolina, 1977

Stand-age class (years)	All types	Forest type				
		Pine plantations	Natural pine	Oak-pine	Upland hardwood	Lowland hardwood
	Acres					
0–9	577,094	153,051	113,014	117,216	189,619	4,194
10–19	495,296	148,603	224,492	38,661	75,919	7,621
20–29	650,273	77,260	434,591	59,250	66,936	12,236
30–39	866,408	16,750	448,262	148,606	212,990	39,800
40–49	948,661	10,266	372,643	151,931	389,396	24,425
50–59	587,657	—	173,580	88,890	320,527	4,660
60–69	212,133	—	51,183	33,605	108,405	18,940
70–79	87,983	—	19,516	22,346	42,783	3,338
80+	102,531	—	12,642	13,095	63,481	13,313
All classes	4,528,036	405,930	1,849,923	673,600	1,470,056	128,527

Table 5.—Average volume of all live timber[1] per acre of commercial forest land by stand-age class, by forest types, Piedmont of South Carolina, 1977

Stand-age class (years)	All types	Forest type				
		Pine plantations	Natural pine	Oak-pine	Upland hardwood	Lowland hardwood
	Cubic feet					
0–9	202	51	242	258	266	—
10–19	853	1,422	645	527	476	986
20–29	1,266	1,943	1,187	1,039	1,181	1,462
30–39	1,552	3,000	1,590	1,307	1,432	1,983
40–49	1,889	2,854	2,100	1,615	1,729	2,433
50–59	1,985	—	2,184	1,770	1,923	2,149
60–69	2,171	—	2,165	2,326	2,001	3,028
70–79	2,184	—	2,623	1,749	1,957	4,641
80+	2,209	—	1,651	2,177	2,006	3,811
All classes	1,462	1,144	1,487	1,260	1,524	2,300

[1] Trees 5.0 inches d.b.h. and larger.

forest qualifying as good habitat ranged from 55 percent in Anderson County to only 18 percent in Chester and Fairfield Counties (table 9).

Previous estimates of the extent of habitat suitable for the red-cockaded woodpecker have been based largely on limited field studies, localized surveys, and generalized forest types. In 1975, a new estimating procedure was developed using RRE data to systematically identify favorable red-cockaded habitat across the entire Southeast. Wildlife experts knowledgeable about habitat requirements of the red-cockaded woodpecker provided descriptive information. The following criteria were used to scan computer tapes of recorded plot data: commercial forest land, pine forest types, sawtimber stands, stand age of 40 years or more, and basal area of 20 square feet or more.

Table 6.—Average volume of sawtimber per acre of commercial forest land by stand-age class, by forest types, Piedmont of South Carolina, 1977

Stand-age class (years)	All types	Forest type				
		Pine plantations	Natural pine	Oak-pine	Upland hardwood	Lowland hardwood
			Board feet[1]			
0–9	313	—	405	480	397	—
10–19	1,345	1,802	1,110	1,675	853	2,006
20–29	2,243	3,233	2,281	1,198	1,876	2,109
30–39	3,674	10,890	4,086	2,554	2,925	3,627
40–49	5,166	11,262	6,864	3,947	3,695	6,835
50–59	5,775	—	7,632	4,504	5,053	3,155
60–69	7,276	—	8,374	8,555	5,932	10,494
70–79	7,516	—	10,649	5,512	5,660	21,706
80+	7,940	—	7,057	9,161	6,241	16,093
All classes	3,750	2,072	4,201	3,102	3,659	6,630

[1] International ¼-Inch Rule.

Table 7.—Average number of saplings[1] per acre of commercial forest land by stand-age class, by forest types, Piedmont of South Carolina, 1977

Stand-age class (years)	All types	Forest type				
		Pine plantations	Natural pine	Oak-pine	Upland hardwood	Lowland hardwood
			Number			
0–9	487	426	721	492	360	100
10–19	771	535	851	1,044	906	450
20–29	796	318	865	1,129	633	567
30–39	734	400	768	788	730	300
40–49	626	250	627	791	590	300
50–59	643	—	686	621	630	200
60–69	527	—	592	720	522	500
70–79	574	—	525	720	522	500
80+	496	—	533	766	467	333
All classes	664	442	751	743	596	386

[1] Trees 1.0 to 4.9 inches d.b.h.

The screening procedure was done in steps. We first identified all sample plots assigned a pine forest type (fig. 5). We sequentially added additional criteria, eliminating plots each time until all the constraints had been imposed. Then, a final map (fig. 6) and statistical table (table 10) were generated.

Habitat variables for the red-cockaded woodpecker are being refined. After these refinements are made, the data can be rescreened for improved estimates of suitable habitat.

For range, we can relate the forage component of the forest resource to broad forest type and stand age. For all forest types, forage yield is high when stands are established and decreases rapidly to age 20 (fig. 7). At this time, the tree

Table 8.—Gray squirrel habitat suitability by stand-age class, by forest type, Piedmont of South Carolina, 1977

Stand-age class (years)	All classes	Forest type			
		Pine plantations	Natural pine	Oak-pine	Hard-wood
	.... *Habitat ranking*[1]				
0–9	0.6	0.5	0.6	0.8	0.8
10–19	1.3	1.3	1.2	1.1	1.4
20–29	2.1	1.5	1.6	2.1	2.5
30–39	2.1	2.0	1.8	2.3	2.6
40–49	2.5	—	2.2	2.6	2.7
50–59	2.7	—	2.3	2.7	2.9
60–69	2.7	—	2.4	2.6	2.9
70–79	2.8	—	2.7	2.8	2.8
80+	2.7	—	2.5	2.7	2.8
All classes	2.0	1.0	1.8	2.1	2.5

[1] 0 = Unsuited.
1 = Poor.
2 = Fair.
3 = Good.

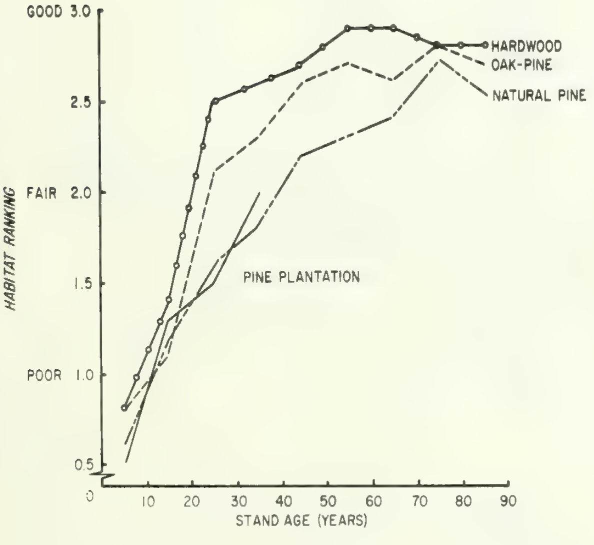

Figure 4.—Gray squirrel habitat suitability, by stand-age class and forest type, Piedmont, South Carolina, 1977.

canopy is usually fully closed and competition for light, moisture, and nutrients is intense. It often remains so until the stand is very old. Forage production in hardwood stands is generally greater than production in pine plantations. For the Survey Unit, hardwood stands experience the highest grazing use (fig. 8). Grazing use is highest in Cherokee County and lowest in McCormick county (table 11).

We think that many characteristics of forest stands will prove important in determining recreational value. One of the items of special interest tallied on each plot is evidence of human recreational use. This evidence included such things as hiking trails, shotgun shells, tree stands, campfire rings, bait containers, trail-bike tire tracks, or other visual evidence of use by people. From this information we can obtain relative estimates of those forest conditions which people seemingly prefer for dispersed outdoor recreation. The information is not intended to measure actual use.

We find that 40 percent of the use by people occurred in two age classes (30 to 39 and 40 to 49 years) (table 12). In addition, 48 percent of all recreational use took place in hardwood stands, 32 percent in natural pine, 16 percent in oak-pine and 4 percent in pine plantations (fig. 9). Spartanburg County had the highest percentage of use and Newberry County the lowest in the Piedmont Unit (table 13).

RRE field crews collected hydrological and soils data that can be used to develop general information about the condition of the resources and to define general trade-offs between various resource management strategies. The following are some examples of analyses that can be made from RRE data.

Average humus and litter depths at various stand ages are shown by forest type in figures 10

Table 9.—Area of commercial forest land and its percentage distribution by habitat quality for gray squirrel, by county, Piedmont of South Carolina, 1977

County	All classes	Quality of squirrel habitat			
		Unsuited	Poor	Fair	Good
	Acres	*Percent*			
Abbeville	219,883	7	28	24	41
Anderson	208,201	1	9	35	55
Cherokee	154,802	17	15	31	37
Chester	290,619	10	25	47	18
Edgefield	234,637	18	18	38	26
Fairfield	386,015	8	30	44	18
Greenville	278,448	—	20	28	52
Greenwood	205,672	7	38	33	22
Lancaster	235,604	14	21	29	36
Laurens	305,701	11	21	37	31
McCormick	206,778	12	21	37	30
Newberry	315,829	4	20	47	29
Oconee	280,294	2	19	37	42
Pickens	209,464	7	18	31	44
Saluda	187,758	8	20	44	28
Spartanburg	271,227	10	20	35	35
Union	272,352	10	23	35	32
York	264,752	2	28	31	39
All counties	4,528,036	8	23	36	33

Table 10.—Area with potential habitat for the red-cockaded woodpecker, by State and ownership class, Southeast

State	All ownerships	National Forest	Other public	Forest industry[1]	Other private
	Thousand acres				
Florida	320	94	36	76	114
Georgia	885	53	75	130	627
South Carolina	705	151	39	88	427
North Carolina	1,406	32	118	138	1,118
Virginia	478	—	16	135	327
Southeast	3,794	330	284	567	2,613

[1] Includes other private lands under long-term lease.

and 11. Figure 10 suggests that topsoil development is slower under planted pine than under other timber types. It is apparent in figure 11 that pine litter accumulates rapidly but decomposes slowly. Hence, topsoil development is slower in pine plantations than in hardwood stands.

In the Piedmont Unit, the highest incidence of soil erosion occurred in Cherokee County and the lowest in Oconee County (fig. 12 and table 14). Table 15 shows a breakdown of soil-texture classes by county. These data may be valuable in explaining erosion or site productivity.

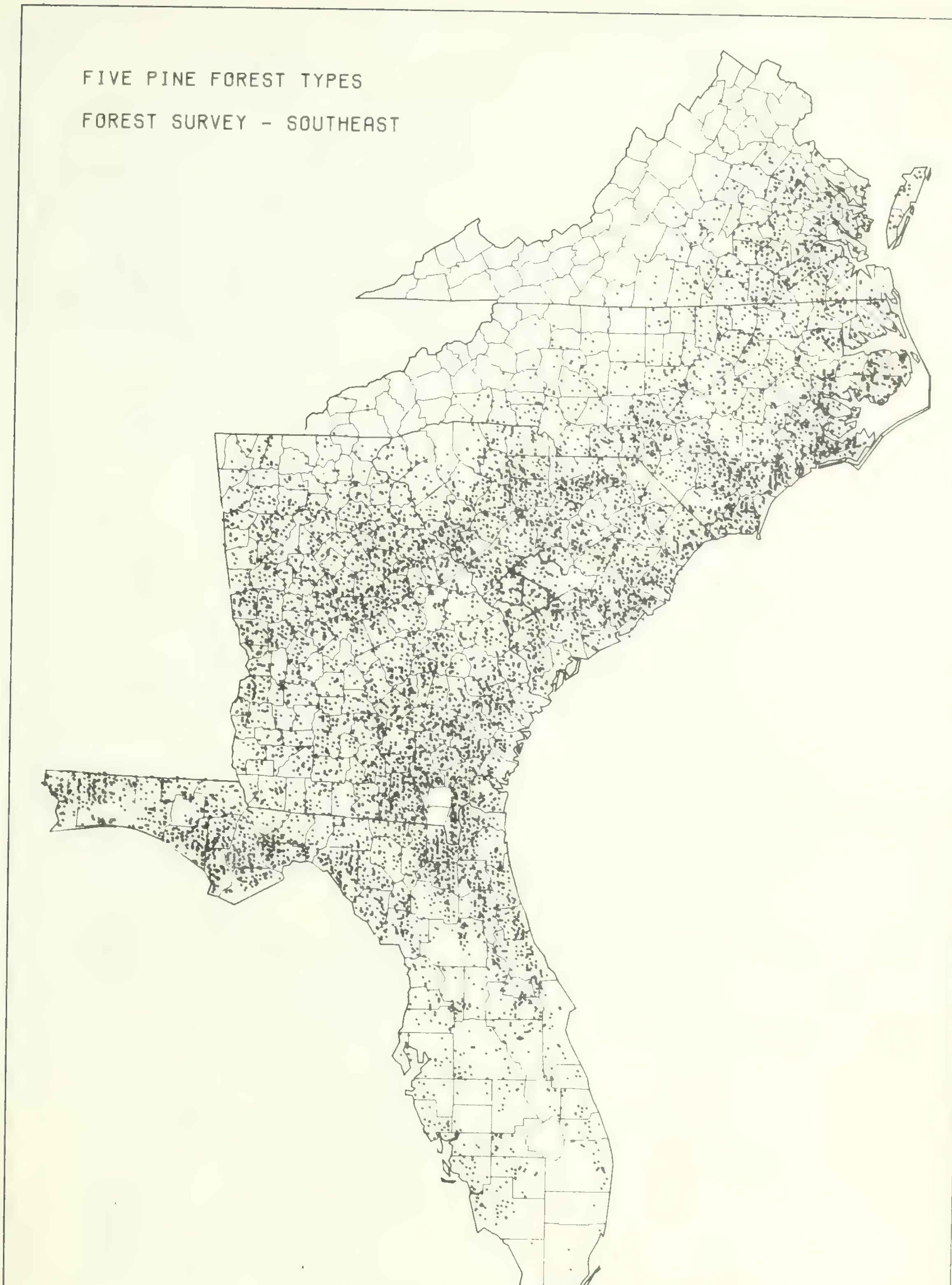

Figure 5.—RRE sample plots assigned a pine forest type, Southeast.

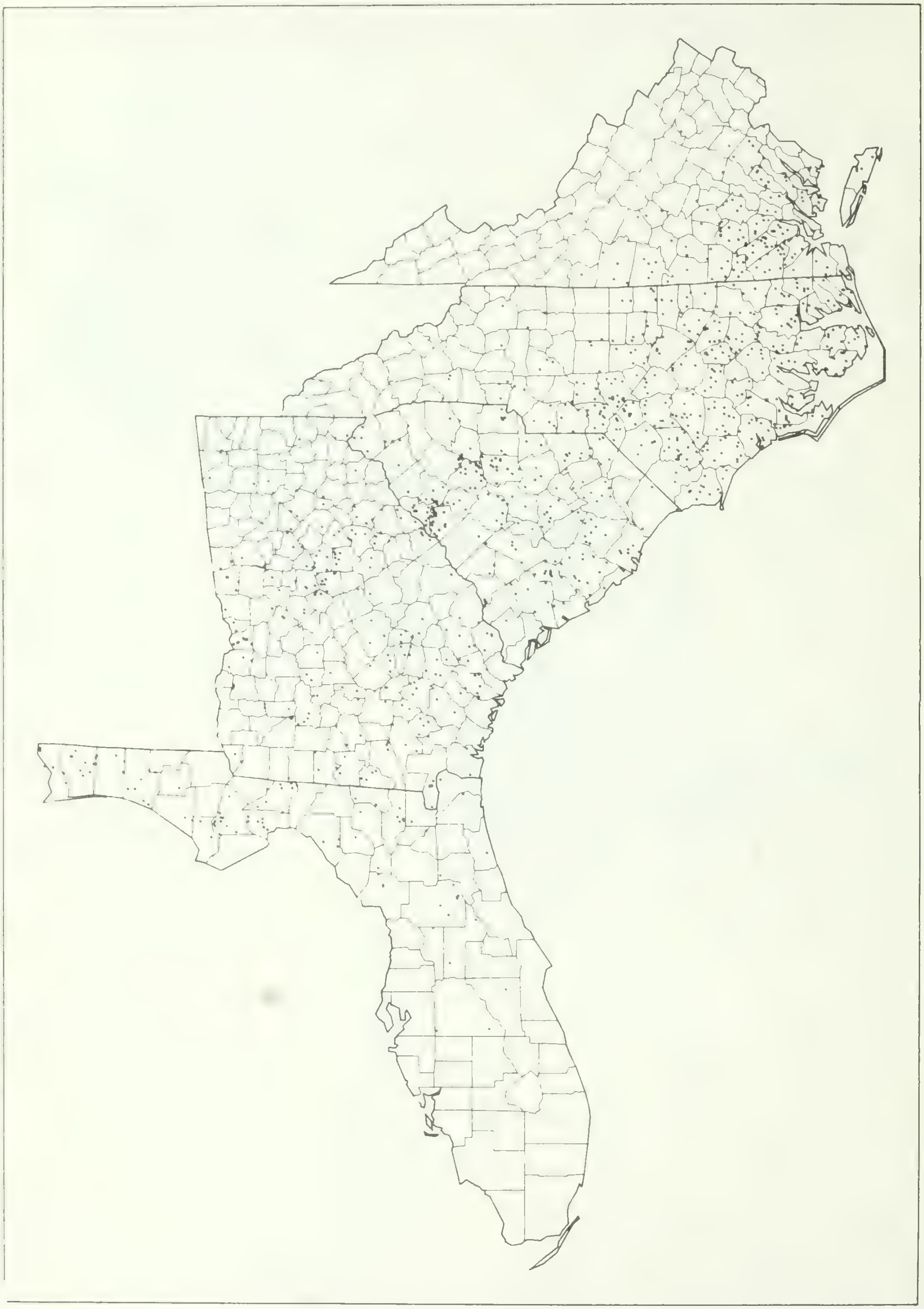

Figure 6.—Potential habitat for the red-cockaded woodpecker, Southeast.

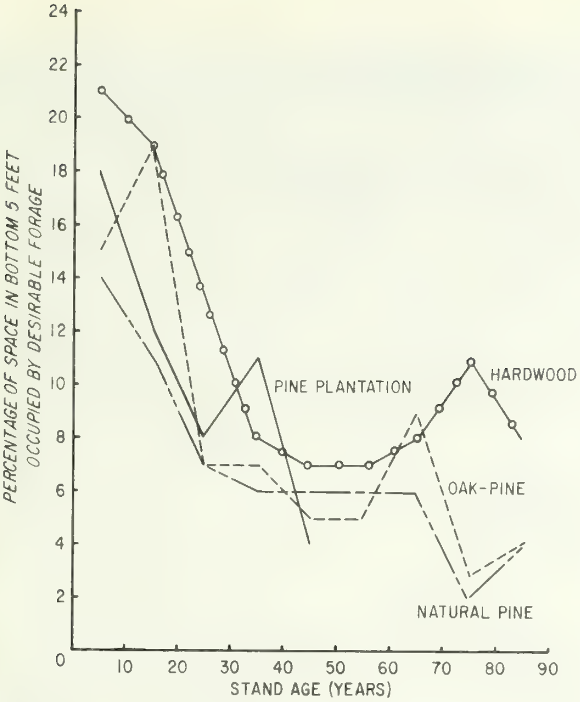

Figure 7.—Percentage of desirable forage, by forest type, by stand age, Piedmont, South Carolina, 1977.

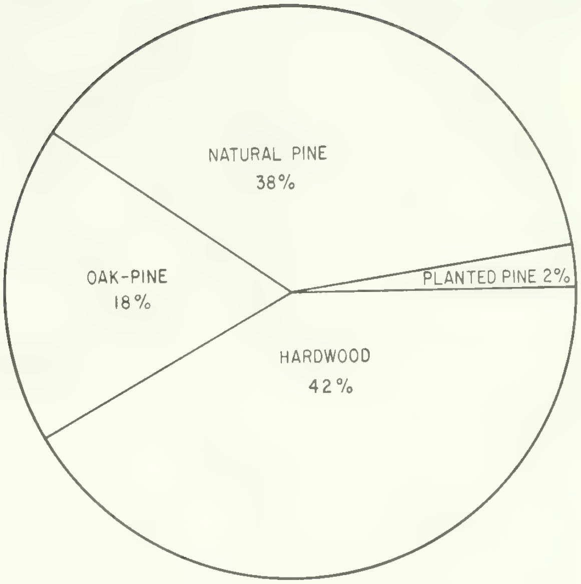

Figure 8.—Percentage of grazed commercial forest land, by forest type, Piedmont of South Carolina, 1977.

Table 11.—Area of commercial forest land and its percentage distribution, by grazing intensity and county, Piedmont of South Carolina, 1977

County	All classes	Grazing intensity[1]			
		None	Light	Medium	Heavy
	Acres		*Percent*		
Abbeville	219,883	82	12	6	—
Anderson	208,201	83	10	5	2
Cherokee	154,802	79	15	6	—
Chester	290,619	91	5	4	—
Edgefield	234,637	98	2	—	—
Fairfield	386,015	89	7	3	1
Greenville	278,448	92	4	4	—
Greenwood	205,672	90	8	—	2
Lancaster	235,604	96	2	2	—
Laurens	305,701	87	10	2	1
McCormick	206,778	99	—	1	—
Newberry	315,829	93	3	—	4
Oconee	280,294	97	2	1	—
Pickens	209,464	90	6	4	—
Saluda	187,758	90	2	3	5
Spartanburg	271,227	88	7	3	2
Union	272,352	82	14	4	—
York	264,752	85	12	3	—
All counties	4,528,036	90	6	3	1

[1] None = No evidence of grazing.
Light = Less than 35 percent of plants grazed.
Medium = 35 to 70 percent of plants grazed.
Heavy = More than 70 percent of plants grazed.

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Table 12.—Use by people, by stand-age class and forest type, Piedmont of South Carolina

Stand-age class (years)	All classes	Forest type			
		Pine plantations	Natural pine	Oak-pine	Hardwood
	Percent use				
0–9	8	27	7	9	5
10–19	10	48	13	9	5
20–29	18	25	36	16	4
30–39	20	—	19	21	22
40–49	20	—	11	26	27
50–59	16	—	10	10	26
60–69	4	—	4	3	5
70–79	2	—	—	3	2
80+	2	—	0	3	4
All classes	100	100	100	100	100

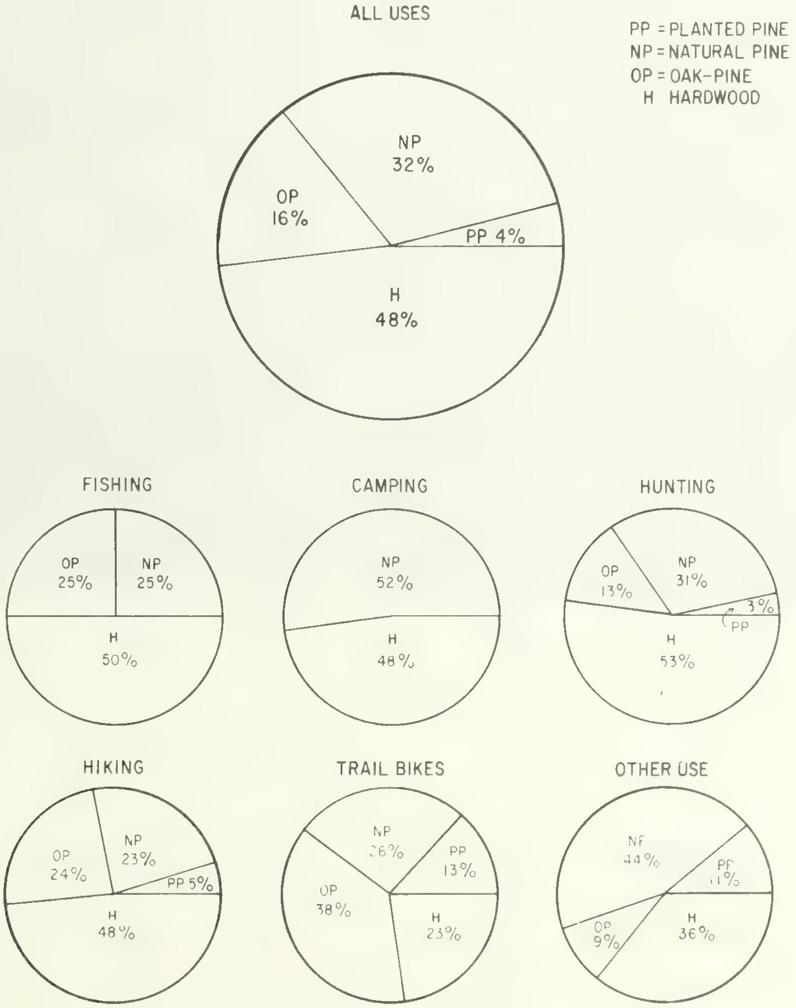

Figure 9.—Distribution of evidence of dispersed outdoor recreation on commercial forest land, by use, by forest type, Piedmont of South Carolina, 1977.

Table 13.—Area of commercial forest land and its percentage distribution of use by people, by county, Piedmont of South Carolina, 1977

County	All classes	No people use	People use
	Acres	.... *Percent* ...	
Abbeville	219,883	82	18
Anderson	208,201	58	42
Cherokee	154,802	70	30
Chester	290,619	93	7
Edgefield	234,637	90	10
Fairfield	386,015	88	12
Greenville	278,448	68	32
Greenwood	205,672	86	14
Lancaster	235,604	93	7
Laurens	305,701	76	24
McCormick	206,778	90	10
Newberry	315,829	99	1
Oconee	280,294	78	22
Pickens	209,464	69	31
Saluda	187,758	85	15
Spartanburg	271,227	50	50
Union	272,352	75	25
York	264,752	83	17
All counties	4,528,036	80	20

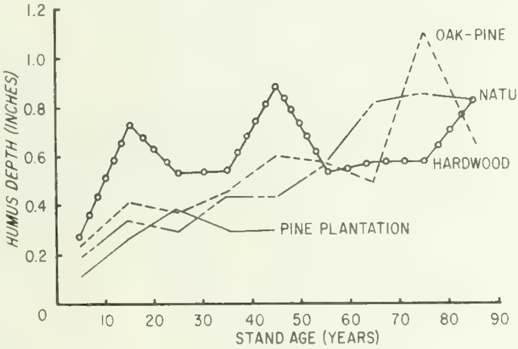

Figure 10.—Average humus depth, by forest type, by stand age, Piedmont of South Carolina, 1977.

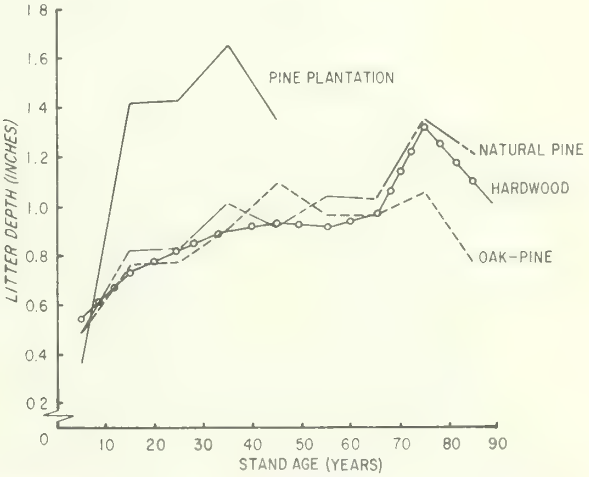

Figure 11.—Average litter depth, by forest type, by stand age, Piedmont of South Carolina, 1977.

Table 16 shows a soil and water risk classification for interpreting potential soil- and water-quality trade-offs. Approximately 1.3 million acres of land need some sort of silvicultural practice during the next 10 years (table 16). These practices are needed to increase timber supply, but what are the risks to soil and water quality? It is apparent from table 16 that the type of silvicultural practice used to take advantage of the opportunity will influence soil and water quality. For example, stand conversion and artificial regeneration with site preparation could be applied on 507,406 acres. If risk class 3 and above were judged unacceptable impacts, intensive site preparation would be acceptable on 328,581 acres and unacceptable on 178,825 acres. For the unacceptable acres, some other regeneration technique with lower risks should be used.

From the standpoint of total wood fiber, the conventional forest inventory measures of grow-

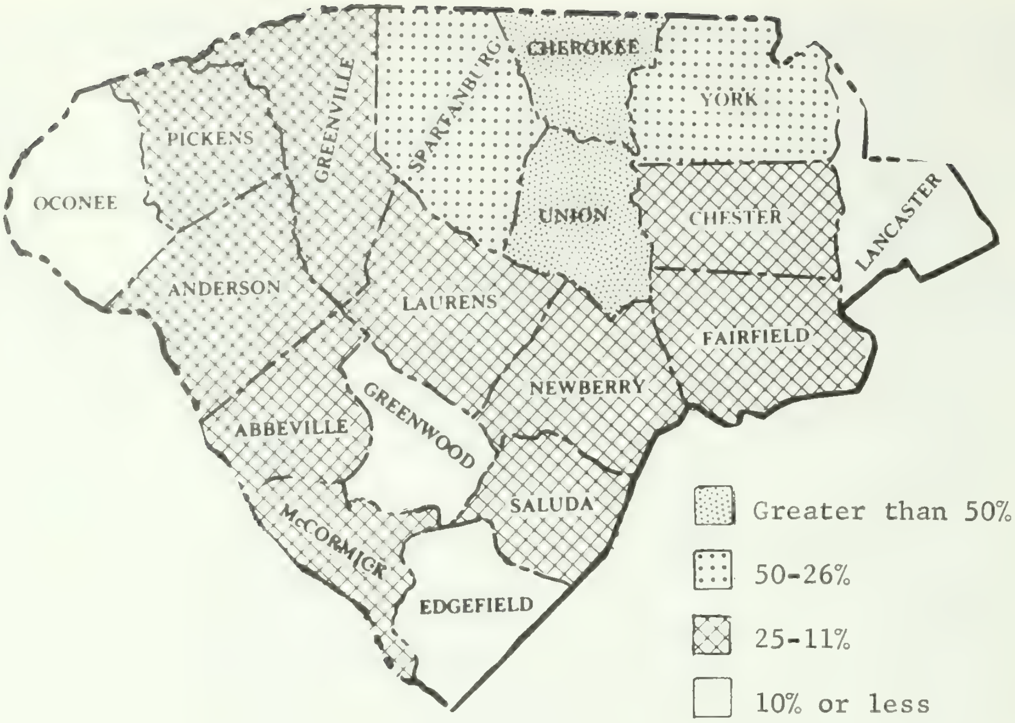

Figure 12.—Proportion of commercial forest with soil erosion, by county, Piedmont of South Carolina, 1977.

Table 14.—Area of commercial forest land and its percentage distribution by degree of soil erosion, by county, Piedmont of South Carolina, 1977

County	All classes	Degree of soil erosion			
		None	Low	Medium	High
	Acres	....	*Percent*	....	
Abbeville	219,883	85	8	2	5
Anderson	208,201	83	12	5	—
Cherokee	154,802	38	28	22	12
Chester	290,619	89	9	—	2
Edgefield	234,637	94	2	2	2
Fairfield	386,015	80	17	2	1
Greenville	278,448	81	8	7	4
Greenwood	205,672	94	6	—	—
Lancaster	235,604	90	6	—	4
Laurens	305,701	88	7	3	2
McCormick	206,778	75	12	9	4
Newberry	315,829	89	10	—	1
Oconee	280,294	95	2	—	3
Pickens	209,464	88	10	—	2
Saluda	187,758	85	15	—	—
Spartanburg	271,227	61	22	10	7
Union	272,352	43	17	18	22
York	264,752	69	19	9	3
All counties	4,528,036	80	12	4	4

Table 15.—Area of commercial forest land and its percentage distribution by soil-texture class, by county, Piedmont of South Carolina, 1977

County	All classes	Soil texture class				
		Sands	Sandy loam	Loam	Clay loam	Clay
	Acres	*Percent*				
Abbeville	219,883	4	22	27	27	20
Anderson	208,201	5	28	49	13	5
Cherokee	154,802	3	33	17	35	12
Chester	290,619	2	26	—	57	15
Edgefield	234,637	16	24	46	12	2
Fairfield	386,015	28	31	5	19	17
Greenville	278,448	2	32	53	11	2
Greenwood	205,672	5	21	40	12	22
Lancaster	235,604	9	23	7	40	21
Laurens	305,701	1	32	37	12	18
McCormick	206,778	1	30	27	26	16
Newberry	315,829	27	14	1	46	12
Oconee	280,294	8	43	13	31	5
Pickens	209,464	2	29	55	13	1
Saluda	187,758	12	15	48	25	—
Spartanburg	271,227	5	34	29	22	10
Union	272,352	7	33	40	20	—
York	264,752	—	34	12	46	8
All counties	4,528,036	8	28	28	26	10

ing stock have been rather conservative. They have included the solid-wood content between a 1-foot stump and a minimum 4.0-inch top of only the central stems in selected trees 5.0 inches d.b.h. and over. Substantial volumes in rough and rotten trees, stumps, tops, limbs, and saplings are excluded. With the gradual trend toward closer utilization and renewed interest in the use of wood for fuel, there is a need for inventories of total wood fiber.

Table 17 shows the distribution of total aboveground volume of all trees on commercial forest land, by class and species group, in the Piedmont of South Carolina. Table 18 shows the per-acre distribution of this total volume by stand-age class for major forest types. The largest differences between conventional measures of growing stock and measures of total volume occur in hardwoods. Table 19 shows a more refined distribution of hardwood timber volume by 1-inch d.b.h. classes and class of material. With the accumulation of data from a special volume study conducted as a subsample in conjunction with the ongoing inventory, average tree characteristics can now be developed for each major species in the Region (table 20). The collection of data on the lesser vegetation is still another step toward the ultimate objective—to be able to quantify total biomass within the forests across the range of forest conditions.

The multiresource inventory provides a wealth of information for studying the ecology of various plant species. The frequency of occurrence of a particular species can be related to various forest types, conditions, and species associations. This kind of information helps to identify the environment required for the growth and development of certain species and to study successional changes that occur within a particular plant community over time. Table 21 shows the distribution and ranking of the five most prevalent species or species groups observed within oak-hickory stands in the Piedmont of South Carolina. The species composition within five vegetative layers is compared over time using 20-year-age classes. Table 22 gives the frequency

Table 16.—Area of commercial forest land and its percentage distribution, by soil- and water-quality risk class, by treatment opportunity, Piedmont of South Carolina, 1977

Treatment opportunity	All classes	Soil- and water-quality risk classes[1]				
		1	2	3	4	5
	Acres	*Percent*				
No treatment	3,223,011	25	39	16	18	2
Salvage cut	39,304	41	20	39	—	—
Harvest	209,064	20	32	7	24	17
Commercial thinning	212,896	52	40	4	4	—
Precommercial thinning	32,590	43	28	13	16	—
Cleaning and release	285,150	25	41	16	17	1
Stand conversion	155,948	23	45	14	15	3
Artificial regeneration without site preparation	18,615	64	29	—	7	—
Artificial regeneration after site preparation	351,458	32	31	10	24	3
Total	4,528,036	27	38	14	18	3

[1] Definitions for soil- and water-quality risk classes:

1. During the recovery period of the activity, the water quality impact should be slight (suspended sediment less than 100 milligrams per liter) and soil erosion less than the rate of new soil development.
2. Water quality during the recovery period of the activity can be impaired (suspended sediment greater than 100 milligrams per liter), but soil erosion should not exceed the rate of new soil development.
3. Water-quality impact can be high and soil erosion can exceed the rate of new soil development during the recovery period of the silvicultural activity.
4. Water-quality impact can be serious and soil erosion can exceed the rate of new soil development for 5 to 20 years after treatment.
5. Water-quality impact can be very serious and soil erosion can exceed the rate of new soil development for more than 20 years after treatment.

of occurrence of major species on plots in the oak-hickory type, again by stand-age class.

In multiple-use management, a diversity of conditions must be maintained. The diversity of forest ecosystems must be sufficient to accommodate the production of the desired combination of human benefits. These benefits include coniferous and hardwood timber products, outdoor recreation, solitude, clean water, and habitat for all endemic plants and animals.

In multiresource inventories, one objective is to measure forest diversity in some way. In the South Carolina inventory, crews recorded important items related to forest diversity within a 450-acre circular area around each sample plot on commercial forest: (1) the percentage of forest, and (2) the number of different forest conditions distinguishable on aerial photographs. Table 23 shows the results of the classifications made at 1,019 sample plots in the Piedmont. At 67 percent of the sample locations, more than 75 percent of the surrounding 450-acre area was forested. At 50 percent of the sample locations, three different forest conditions occurred within the surrounding 450-acre area.

Finally, we reemphasize that the analysis of the multiresource inventory data collected in South Carolina is outside the scope of this Paper. In this chapter, we have merely given examples of the sorts of information that were gathered and the ways in which the information might be reported.

Table 17.—Total aboveground volume of all trees on commercial forest land, by class and species group, Piedmont of South Carolina, 1977

Class of volume	All species	Pine	Other softwood	Soft hardwood	Hard hardwood
	Thousand cubic feet				
Sapling-size trees:					
Growing-stock	824,931	405,015	69,677	160,335	189,904
Non growing-stock	414,452	40,826	10,662	131,144	231,820
Total	1,239,383	445,841	80,339	291,479	421,724
Growing-stock trees:					
Poletimber-size trees					
Stumps	182,900	87,772	2,987	30,255	61,886
Bolewood	2,067,400	1,004,371	34,178	417,164	611,687
Tops and limbs	416,266	242,669	8,258	57,470	107,869
Total	2,666,566	1,334,812	45,423	504,889	781,442
Sawtimber-size trees					
Stumps	189,715	105,335	2,297	40,183	41,900
Saw log portion	3,129,476	1,847,916	40,291	523,660	717,609
Upper-stem portion	428,041	215,224	4,693	78,151	129,973
Tops and limbs	342,845	153,628	3,349	60,748	125,120
Total	4,090,077	2,322,103	50,630	702,742	1,014,602
Rough and rotten trees:					
Stumps	55,782	7,949	411	18,456	28,966
Bolewood	542,794	77,857	4,021	174,598	286,318
Tops and limbs	133,139	18,595	960	53,243	60,341
Total	731,715	104,401	5,392	246,297	375,625
Total, all volume classes	8,727,741	4,207,157	181,784	1,745,407	2,593,393

Table 18.—Average total aboveground volume of wood[1] per acre of commercial forest land by stand-age class, by forest types, Piedmont of South Carolina, 1977

Stand-age class (years)	All types	Forest type				
		Pine plantations	Natural pine	Oak-pine	Upland hardwood	Lowland hardwood
	Cubic feet					
0–9	390	218	505	464	403	9
10–19	1,271	1,923	1,037	883	841	1,372
20–29	1,791	2,432	1,728	1,604	1,593	2,064
30–39	2,085	3,377	2,131	1,866	1,968	2,383
40–49	2,397	3,181	2,606	2,146	2,235	2,947
50–59	2,503	—	2,686	2,307	2,446	2,530
60–69	2,660	—	2,598	2,807	2,499	3,637
70–79	2,652	—	3,099	2,238	2,395	5,253
80+	2,646	—	1,982	2,630	2,457	4,265
All classes	1,923	1,515	1,976	1,727	1,981	2,767

[1] Trees 1.0 inches d.b.h. and larger, excluding bark.

Table 19.—Average aboveground cubic-foot volume in hardwoods, by d.b.h. class and volume material class, Piedmont of South Carolina, 1977

Diameter class (inches)	Total aboveground volume	Bole volume[1]			Crown volume	
		Stump	Saw log portion	Upper stems	Tops	Limbs[2]
	Cubic feet					
1	0.12	0.02	—	—	0.09	0.01
2	.44	.06	—	0.01	.35	.02
3	1.05	.11	—	.12	.78	.04
4	1.85	.20	—	.81	.71	.13
5	2.95	.26	—	1.61	.76	.32
6	5.07	.39	0.02	3.86	.66	.14
7	7.79	.54	.14	5.78	.61	.72
8	9.86	.71	.95	6.97	.65	.58
9	12.13	.90	2.63	6.93	.62	1.05
10	18.47	.87	8.21	7.10	.92	1.37
11	21.74	1.22	11.99	5.80	.86	1.87
12	29.70	1.60	17.38	6.17	1.33	3.22
13	35.56	1.72	23.71	5.26	1.03	3.84
14	43.21	2.02	28.88	6.09	1.02	5.20
15	51.79	2.25	37.58	6.88	1.02	4.06
16	56.55	2.36	42.51	5.94	1.68	4.06
17	65.13	1.72	47.77	9.47	1.05	5.12
18	96.94	3.11	70.51	10.87	4.10	8.35
19	87.47	3.70	64.63	5.45	1.14	12.55
20	101.52	3.58	73.48	8.44	1.38	14.64

[1] Includes both mainstem and fork volume to a 4.0-inch top outside bark.

[2] Includes limbs of all sizes.

Table 20.—Average tree characteristics for loblolly pine in the Southeast

DBH class	Double bark at d.b.h.	Lengths			Cubic-foot volume		Board-foot volume[1]
		Total height	Bole length	Saw log length	Merchantable volume	Total volume	
	Inches	....	*Feet*	....	... *Cubic feet*	...	
5	0.95	39.4	16.9	—	1.76	2.47	—
6	1.06	44.2	24.5	—	3.22	3.95	—
7	1.20	48.2	30.3	—	4.96	5.78	—
8	1.29	53.5	36.9	—	7.40	8.30	—
9	1.40	58.4	42.9	24.6	10.49	11.49	36.3
10	1.49	62.7	47.9	32.9	14.02	15.17	58.7
11	1.62	65.2	50.8	38.2	17.63	18.96	82.6
12	1.70	67.5	53.5	42.5	21.62	23.14	108.9
13	1.76	70.0	56.4	46.6	26.25	27.94	139.6
14	1.85	73.5	60.0	50.5	31.69	33.62	176.2
15	1.92	75.2	62.2	53.5	37.14	39.25	215.5
16	2.03	77.4	63.8	55.7	43.30	45.71	259.6
17	2.06	77.2	63.8	56.1	48.58	51.40	299.3
18	2.18	82.1	68.8	61.0	57.74	60.61	364.4
19	2.27	76.3	63.3	55.9	59.04	62.29	378.1
20	2.40	84.3	70.8	64.0	71.54	75.27	464.4

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[1] International ¼-Inch Rule.

Table 21.—Distribution of plant species by age class and vegetative layer for oak-hickory stands, Piedmont of South Carolina, 1977

Vegetative layer	Age class (years)	Ranking of five most prevalent species				
		First	Second	Third	Fourth	Fifth
Overstory (30+ feet)	0–19	Sweetgum	Yellow-poplar	Loblolly pine	Red maple	White oak
	20–39	White oak	Yellow-poplar	Sweetgum	Hickory	Scarlet oak
	40–59	White oak	Yellow-poplar	Sweetgum	Hickory	Southern red oak
	60–79	Yellow-poplar	Sweetgum	Hickory	White oak	Black oak
	80+	Hickory	White oak	Chestnut oak	Sweetgum	Yellow-poplar
Midstory (15–30 feet)	0–19	Sweetgum	Elm	Loblolly pine	Red maple	Water oak
	20–39	White oak	Sweetgum	Hickory	Red maple	Post oak
	40–59	White oak	Hickory	Sweetgum	Red maple	Water oak
	60–79	White oak	Hickory	Red maple	Black oak	Sweetgum
	80+	Hickory	White oak	Hackberry	Beech	Sourwood
Understory (5–15 feet)	0–19	Dogwood	Sweetgum	Redcedar	Elm	Red maple
	20–39	Sweetgum	Dogwood	Hickory	White oak	Honeysuckle
	40–59	Dogwood	Red maple	Hickory	Sweetgum	Blue beech
	60–79	Dogwood	Hickory	Elm	Other shrubs	Red maple
	80+	White oak	Yellow-poplar	Laurel	Dogwood	Blackgum (upland)
Shrub layer (1–5 feet)	0–19	Honeysuckle	Greenbrier	Sweetgum	Blackberry	Dogwood
	20–39	Honeysuckle	Greenbrier	Wild grape	Blackberry	Dogwood
	40–59	Laurel	Red maple	Dogwood	Honeysuckle	Hickory
	60–79	Other shrubs	Switch-cane	Laurel	Honeysuckle	Dogwood
	80+	Laurel	Switch-cane	Red maple	Hickory	Dogwood
Ground layer (0–1 foot)	0–19	Other grasses	Honeysuckle	Forbs	Blackberry	Greenbrier
	20–39	Honeysuckle	Greenbrier	Poison ivy	Other grasses	Forbs
	40–59	Honeysuckle	Forbs	Wild grape	Other grasses	Greenbrier
	60–79	Forbs	Honeysuckle	Ferns	Other grasses	Poison ivy
	80+	Forbs	Switch-cane	Blueberry	Ferns	Other grasses

Table 22.—Major species of plant groups in the oak-hickory forest type and their frequency of occurrence, by stand-age class, Piedmont of South Carolina, 1977

Plant species	All age classes	Stand-age class				
		0–19	20–39	40–59	60–79	80+
	.... *Percentage of sample locations*					
Honeysuckle	63	70	62	65	53	29
Greenbrier	79	78	82	82	70	71
Sweetgum	70	74	68	71	63	57
Blackberry	38	70	42	27	23	14
Dogwood	80	63	82	84	87	86
Forbs	89	83	85	90	97	100
Redcedar	46	39	53	51	30	14
Elm	44	52	52	40	37	—
Red maple	80	70	70	88	83	57
Loblolly pine	26	41	28	18	33	29
Water oak	37	39	35	41	30	—
White oak	70	37	75	80	73	86
Yellow-poplar	66	52	62	69	83	71
Other grasses	79	81	72	83	73	71
Poison ivy	54	39	60	58	53	57
Wild grape	82	67	87	88	77	43
Hickory	83	52	88	88	97	100
Post oak	34	30	35	38	23	29
Scarlet oak	34	33	30	36	37	43
Laurel	11	6	7	12	23	29
Blue beech	15	7	12	17	27	29
Southern red oak	53	39	60	60	40	14
Ferns	52	48	42	54	60	86
Other shrubs	52	37	48	59	50	57
Switch-cane	11	11	5	11	13	43
Black oak	41	20	40	49	53	29
Blueberry	37	33	38	38	30	43
Blackgum (upland)	56	43	58	60	67	43
Hackberry	6	2	3	7	7	14
Beech	20	4	27	21	20	43
Sourwood	38	28	32	42	47	57
Chestnut oak	10	4	10	8	23	43

Table 23.—Distribution of samples in commercial forest land, by percent forest and number of forest conditions within a 450-acre circular area around the sample location, Piedmont of South Carolina, 1977[1]

Percent forest within 450-acre circular area	Total number of samples	Number of forest conditions within 450-acre area								
		1	2	3	4	5	6	7	8	9
		Number of samples								
1–5	6	1	—	2	3	—	—	—	—	—
6–15	4	—	2	1	—	1	—	—	—	—
16–25	15	2	2	4	2	—	4	1	—	—
26–35	21	1	3	12	4	—	1	—	—	—
36–45	24	—	4	9	8	—	2	1	—	—
46–55	58	1	8	29	15	2	2	1	—	—
56–65	97	—	7	46	28	8	3	2	2	1
66–75	112	1	7	56	33	7	6	—	1	1
76–85	204	—	12	113	59	11	4	4	1	—
86–100	478	1	55	237	138	37	5	4	1	—
Total	1,019	7	100	509	290	66	27	13	5	2

[1] Intended as one measure of forest diversity and forest habitat interspersion.

ANALYSIS OF THE DATA

The multiresource inventory was begun to provide managers and policymakers with information about renewable forest resources other than timber. For this purpose, field data are not nearly enough. The new data must be analyzed and interpreted.

For the first time, foresters, range scientists, wildlife biologists, recreation specialists, ecologists, and others will be able to draw upon a common data base. This does not mean, however, that all needs can be served by a single analysis. Each discipline will want to evaluate benefits from a different perspective.

We can only hope that all the disciplines will start with a common understanding of the basic ecological relationships. The plant communities that occupy forests and rangelands develop in predictable sequences, and certain benefits can be expected from each stage in the sequence. For example, a stand of young hardwood saplings and seedlings offers no immediate timber benefits, but may offer excellent browse for deer. By cutting and regenerating the stand, we reap the timber benefit and renew the deer browse habitat. However, harvesting also eliminates the mast and dens for squirrels. The scope of resource analysis must be expanded to take these ecological relationships into consideration.

DEVELOPMENTS UNDERWAY

Computer modeling is a useful technique for improving resource analysis. We call attention to the DYNAST system developed at the Southeastern Station (Boyce 1977). DYNAST consists of three complementary models adapted to different management purposes. The timber model, DYNAST-TM, harmonizes management actions for the production of timber. The optimum benefit model, DYNAST-OB, optimizes a specified benefit such as wilderness experience, recreation, visual appeal, habitat for a specific animal or plant, timber, water, or energy production. The multiple benefit model, DYNAST-MB, harmonizes forest management for multiple benefits.

The DYNAST system is based on the relationship between the benefits produced and the distribution of a forest's stands in different stages of development (called habitats). The continuum of succession must be divided into habitats that are significant for the benefits being considered. The classification will vary for different types of forest and can be modified whenever a new relationship is discovered between a particular age class and a particular benefit.

The multiresource inventory being tested in South Carolina seems to provide an ideal classification of forest habitats for input into the DYNAST models. Plans call for analyses of the

South Carolina data using DYNAST.

Currently, resource analysts with RRE in the Southeast are studying the size and age distributions, species composition, and successional trends among the major forest types in South Carolina. Preliminary findings suggest that with few exceptions land-use patterns and forestry practices are fragmenting the forests into smaller parcels or stands. For example, in the Piedmont Region, about 30 percent of the commercial timberland is broken up into distinct forest conditions of less than 10 acres (Knight 1978). There is also mounting evidence of a strong successional trend from pine to hardwood species.

Other developments underway include analyses of the multiresource data from the standpoints of outdoor recreation and wildlife habitat. The outdoor recreation study has been arranged through a cooperative agreement between RRE and Clemson University (Saunders, Stachoviak, and Howard 1978). The wildlife habitat study has been arranged through a cooperative agreement between RRE and Virginia Polytechnic Institute and State University.

The long-term objective of RRE in the Southeast is to develop and maintain expertise required to fully analyze and integrate all resource elements. For the present, our resource analysts who are most familiar with the data should establish the basic ecological relationships and make the initial interpretations of the findings. This procedure will identify the limitations and proper use of the data. After the basic ecological relationships are established, outside researchers are encouraged to help extend the analysis of the data through both independent and cooperative efforts.

THE FUTURE

We are optimistic about the future of multiresource inventories. We have identified an important task and made good progress toward its completion. As future assessments are planned and additional information needs develop, changes are inevitable. Our goal, therefore, is to maintain the expertise needed to make changes while we are collecting, processing, and analyzing resource information for the Southeast.

IMPROVE EACH NEW INVENTORY STARTED

Southeastern States are inventoried in an established sequence. As work in one State nears completion, planning and preliminary inventory work are underway in the next State. In every inventory cycle, however, each State is treated as a new start. Past work is reviewed, procedures are examined, and various changes are made before work is started in the next State. Major changes are usually avoided within a State because inconsistencies in the data within a State would create difficulties in both present and future measurements. We are constantly looking for ways to improve procedures, and we think each new inventory is a little better than the preceding one. By the time a State is revisited, therefore, the accumulated improvements are quite significant.

ESTIMATING FUTURE NEEDS

The frequency of inventories, commonly referred to as the survey cycle, has fluctuated between 8 and 11 years since 1945. If current manpower and sampling intensity are maintained, we will be able to conduct multiresource inventories on an 8-year cycle. Many people argue that the cycle should be reduced to 5 years. Even if this is done, it will take 5 years to uniformly gather a piece of new information across the entire Southeast. To partially offset the timelag between wanting information and having it, the RRE inventory staff tries hard to estimate future needs and to collect data to meet these needs. The record shows that RRE has been fairly successful. For example, biomass studies were initiated in 1963 and the demand for this information has recently intensified. A new class of management-related information, including treatment opportunity, stand history, timber availability, and improved stand age, was added to the inventory in 1970. User interest in this information is now on the increase.

The challenge and risk associated with anticipating future resource-information needs are considerably greater with multiple resources, but so are the potential benefits.

THE 1990 ASSESSMENT

Most of the transition to a multiresource inventory, described in this Paper, was accomplished under stringent deadlines. A response to the RPA was needed; the 1980 Assessment due dates were firm; many separate initiatives already in motion required inventory involvement. Now

that data needs for the 1980 Assessment have largely been satisfied and the South Carolina Pilot Project is nearing completion, it is time to consider what the 1990 Assessment needs will be and how they will be met. Several assumptions can be made in this regard. First, deadlines will be established requiring final data by mid-1988. Further, the Forest Service will want to use the best possible data base, and this base will be shared by various resource uses. We can also speculate that the 1990 Assessment will place much greater emphasis on use interactions and the display of alternatives for mixing and balancing combinations of resource use. If these assumptions hold true, RRE in the Southeast must strengthen both techniques research and resource analysis, and it must conduct multiresource inventories in Florida, Georgia, North Carolina, and Virginia. We expect to complete the initial multiresource inventory of the Southeast by 1985, and to complete a second generation multiresource inventory and remeasurement of South Carolina and Florida by 1988, for use in the 1990 Assessment.

GATHERING ADDITIONAL INFORMATION

As described earlier in this Paper, there are four ways we can gather additional resource information. We can collect additional information at each sample, overlay other data, acquire information already compiled in final form, or initiate special studies. The South Carolina Pilot Study placed emphasis on the first method and greatly increased the amount of data collected at both forest and nonforest sample locations. The next phase of increased data collection will involve the remaining methods of gathering additional information.

The key to overlaying independent data sources is to have common geographic locators. Various mapping and computer techniques can be used to merge information from different sources if a compatible coordinate system is used. Past inventories in the Southeast have used an arbitrary coordinate system sensitive to the nearest mile. A study conducted by RRE (Cost 1976) shows that as location accuracy is increased, the cost also increases. A decision to abandon the existing system in favor of a standard, but more expensive, coordinate system will have to be made if RRE inventory data and data from other sources are to be combined.

Many sources of information are available to the resource analyst. Some of these outside sources are completely reliable, some are not. Despite questions of reliability, we must often use outside sources for types of data that we cannot efficiently collect.

The remaining way to gather additional information is through special studies. Such studies are often used when gathering of certain data is too complicated or too time consuming for regular inventory crews. Special studies may also require expensive, specialized equipment. In these studies, we subsample from the regular inventory plots, or we select an independent sample. New studies will likely be needed to: (1) validate wildlife habitat rankings, (2) develop weight conversion factors for space occupancy stocking estimates, (3) determine average weights per cubic foot for minor tree species, and (4) closely monitor the management actions in harvested pine stands.

REPORTING RESULTS—FUTURE OUTLOOK

We have not yet formulated a strategy for disseminating our results. Perhaps some combination of publications, direct consultation, data transfers, and customized responses will be satisfactory. We really do not know. We do know that when we broadened the scope of our inventories, we also broadened the interested audience. Many of the new users of our results may not yet view us as a source of information. We will continue to look for new ways to make the multiresource inventory as useful and as available as possible. We encourage specialists in ecology, hydrology, outdoor recreation, range, soils, and wildlife to assist and cooperate with RRE in the evaluation and dissemination of the inventory findings.

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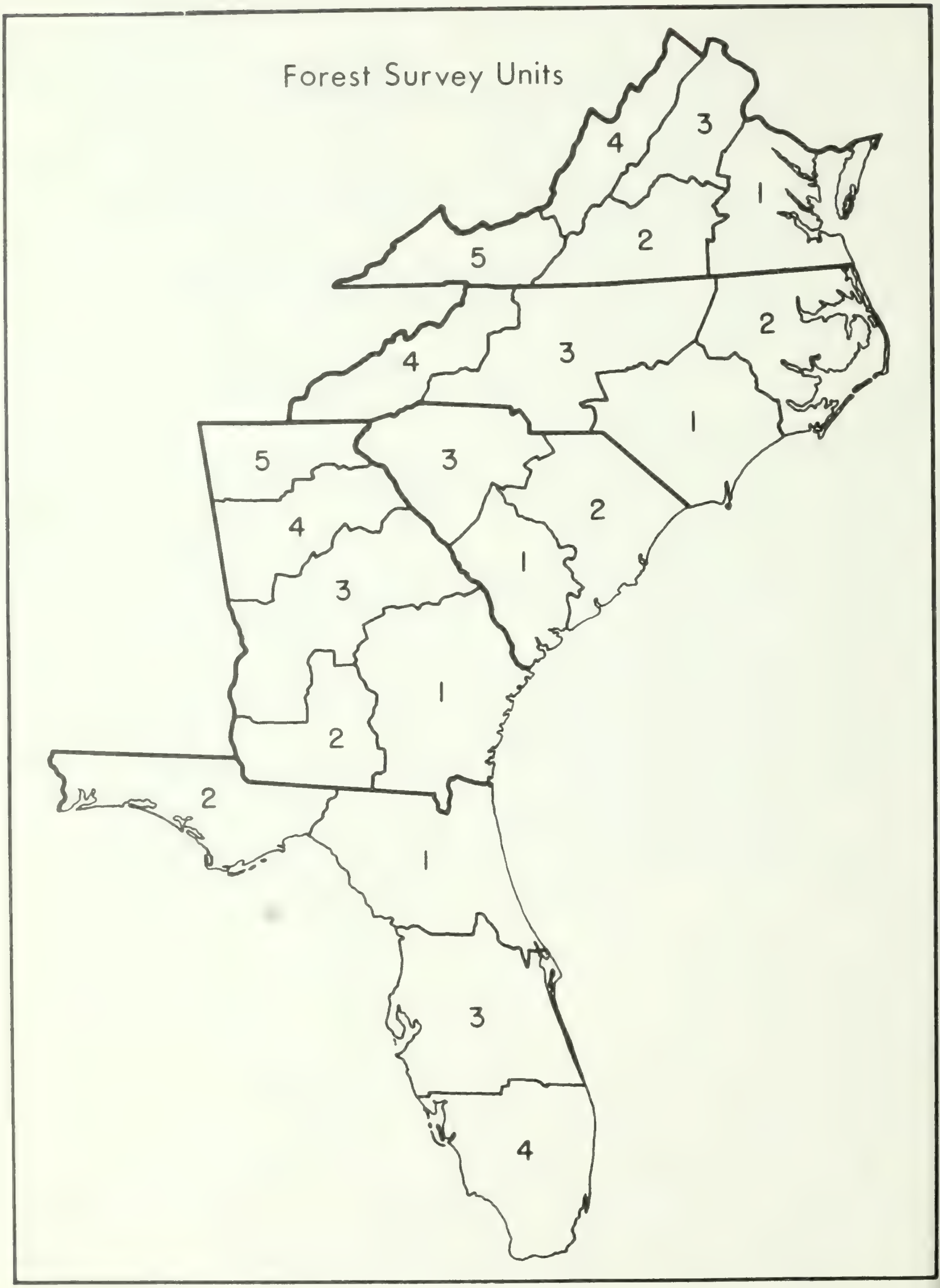
APPENDIX



Forest Survey Units

-1, JANUARY 1976 FOREST INVENTORY TREE RECORD CREW: ______________ DATE: ______________

ATION		TREE				TREE QUALITY					SITE			BARK	SIZE		TREE CLASSIFICATION								
COUNTY	LOCATION	POINT NO.	TREE NO.	SPECIES	D.B.H.	LOG GRADE	CROWN RATIO	CROWN CLASS	DAMAGE	TREE CLASS	SITE CLASS	TREE ORIGIN	PHYSIO.CLASS	DOUBLE BARK AT D.B.H.	TOTAL AGE	TOTAL HEIGHT	FORKS	LIMBS	PRODUCT	NUMBER OF SECTIONS	IDENT.SORY	SURVEY CYCLE	OPTION 1	OPTION 2	OPTION 3
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
XX	XXX	X	XX	XXX	XXX	X	X	X	XX	X	X	X	XX	XXX	XXX	XXX	X	XX	XX	XX	X	X	XX	XX	XX

TREE SECTIONS							TREE LOGS OR BOLTS												OPTIONAL		
			WORK ZONE	SECTION CULL						UTILIZATION			SWEEP			CROOK					
LOWER D.O.B.	UPPER D.O.B.	SECTION LENGTH	ACC. SEC. LGTHS.	PERCENT CU. FT.	PERCENT BD. FT.	MINOR LIMBS	LOG NUMBER	LOG GRADE	BOLTER LOG	UTILIZ.	PRODUCT	DBLE.BARK TOP OF SECTION	DEPARTURE	LENGTH	D.O.B.	DEPARTURE	LENGTH	D.O.B.	OPTION 1	OPTION 2	OPTION 3
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
XXX	XXX	XXX		XXX	XXX	XX	XX	X	X	X	XX	XXX	XX	XXX	XXX	XX	XX	XXX	XX	XX	XX

FORM FS-[illegible], Mar. [illegible]

FOREST RESOURCES INVENTORY SAMPLE RECORD

Page

STATE	[illegible]	COUNTY	LOCATION	SAMPLE KIND	DATE OF SURVEY	L.U. PATTERN	OWNERSHIP	LARGE OWNER CODE	STAND ORIGIN	SITE CLASS	PHYSIO. CLASS	STAND AGE	SEED SOURCE	FOREST TYPE	STAND SIZE	SEEDLINGS PER ACRE		STOCK.		INHIB. CLASS	SLOPE	ASPECT	ACCESSIBILITY	OPERABILITY	SIZE OF FOREST
																SO. Y. PINES	OTHER	NONSTOCK.	INHIB. VEG.						
1	2	3	4	5	6	7	8		10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	2
XX	X	XX	XXX	X	XXXX	X	XX	XX	X	X	XX	XX	X	XX	XX	XX	XX	X	X	X	X	X	X	X	XX

PAST TREAT. OR DIST.				REA. FOR OR.	OLD CLASSIFICATIONS				POINT REMEAS.	INV. POINT	NO. OF ENTRIES	POINT HISTORY			CRUISER NUMBER	OPEN				REMEASUREMENT PERIOD	EXPANSION FACTORS	
[illegible]	PERIOD	SECONDARY	PRIMARY		STAND ORIG.	FOREST TYPE	OWNERSHIP	LAND USE				1	2	3		1	2	3	4		REMEASUREMENT	VOLU
		29	30	31	32	34	35	36	37	38	39	40			41	42				43	44	45
XX	XX	X	X	X	X	XX	XX	X	X	X	XX	X	X	X	XX	XX	XX	XX	XX	XXX	XXXXX	XXXX

[illegible]	[illegible] NUMBER	AZIMUTH	DISTANCE	POINT NUMBER	TREE NUMBER	TREE HISTORY	SPECIES	D.B.H.	TREE CLASS	MGT. CLASS	LENGTH	CUBIC CULL PERCENT	CROWN RATIO	CROWN CLASS	DAMAGE	OLD D.B.H.	CRUISER NUMBER	VOL. IDENT.	LIVE TREE CAVITIES	PROSPECTIVE DEN TREES	OP 5
46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
	XX	XXX	XX	X	XX	X	XXX	XXX	X	X	XXX	XX	X	X	XX	XXX	XX	X	XX	X	XX
	01																				
	02																				
	03																				
	04																				
	05																				
	06																				
	07																				
	08																				
	09																				
	10																				
	11																				
	12																				
	13																				
	14																				
	15																				
	16																				
	17																				
	18																				
	19																				
	20																				

1 ____ 2 ____ 3 ____ 4 ____ 5 ____ 6 ____ 7 ____ 8 ____ 9 ____ 10 ____

ORM SE-3, MARCH 1977

AREA SAMPLE RECORD

Page ______ of ____

TATE ______
XX

NIT ______
X

OUNTY ______
XX

OUNTY NAME ____________________________________

Type of Water/Marsh
1-Fresh
2-Salt

Water Class
1-Lake
2-Stream

Lake Size
1-Less than 1 acre
2-1-5 acres
3-6-10 acres
4-11-15 acres
5-16-20 acres
6-21-25 acres
7-26-30 acres
8-31-35 acres
9-36-40 acres

Stream Width
1-1-30 feet
2-31-110 feet
3-111-190 feet
4-191-270 feet
5-271-350 feet
6-351-430 feet
7-431-510 feet
8-511-590 feet
9-591-660 feet

Sampling Method
Blank - Photo
1- Aerial
2- Ground
3- Deleted

P.I. by ________

Date of P.I. __________

Cruiser Numbers ______, ______, ______, ______

CLUSTER					PHOTO CLASS						SUBSAMPLE FIELD CHECK																PLOTS				
											CLUSTER POINTS																				
OLD PHOTO NUMBER	NEW PHOTO NUMBER	OLD PLOT NUMBER	NEW PLOT NUMBER	CLUSTER NUMBER	COMM. FOREST RESER. FOREST 20:50	UNPRODUCTIVE FOREST 40	OTHER MISC. 60	URBAN 67	CENSUS WATER 91	NON-CENSUS WATER 92	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	OLD LAND USE	NEW LAND USE	FRESH SALT WATER	WATER CLASS	SIZE/WIDTH
XXX	XXX	XXX	XXX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	X	X	X

FORM SE-9, MAY 1977 (REVISED)

ECOLOGICAL DIVERSITY PROFILE RECORD

LOCATION						WILDLIFE HABITAT												WATER					RANGE		RECREATION							
																		TYPE			DEPTH											
STATE	UNIT	COUNTY	LOCATION	CRUISER NUMBER	NUMBER OF ENTRIES	BROWSING	TYPE DIVERSITY	MILL RESIDUES	LOGGING SLASH	LITTER & TRASH	GULLIES	HOLES & CAVES	ROCK OUTCROPS	MARSH CONDITIONS	SPANISH MOSS	SNAGS PER ACRE	# OF CAVITIES	STAND	ACRE	POINT 1	ACRE	POINT 1	GRAZING	FENCING	PEOPLE USE	HIKING	HUNTING	CAMPING	FISHING	TRAIL BIKES	OTHER USE	POSTED
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
XX	X	XX	XXX	XX	XX	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	XX	XX	X	X	X	X	X	X	X	X	X	XX
39																																

SOIL								LAND USE IMPACT						MISC.		OPEN															
LITTER DEPTH	HUMUS DEPTH	SOIL TEXTURE	PERCENT BARE GROUND	PERCENT COMPACTION	SOIL STRUCTURE	SLOPE LENGTH	SOIL EROSION	NONFOREST PROXIMITY		ZONE 1	ZONE 2	ZONE 3	PERCENT FOREST	BURN HISTORY	SEASON	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
35	36	37	38	39	40	41	42	43		44	45	46	47	48	49	50														
XX	XXX	X	XX	XX	X	XXX	X	X	X	X	X	X	X	X	X	X	X	X	X	XX	X	X	X	X	XX	X	X	X	X	XX

VEGETATIVE DATA

			HEIGHT			BROAD CLASS											
ENTRY NO.	POINT NO.	HT. ZONE	FROM	TO	ZONE PERCENT	SPECIES	PERCENT	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES	SPECIES
59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76
XX	X	X	XX	XX	XXX	X	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
01																	
02																	
03																	
04																	
05																	
06																	
07																	
08																	
09																	
10																	
11																	
12																	
13																	
14																	
15																	
16																	
17																	
18																	
19																	

COMMON NAME

YELLOW PINES

Loblolly pine
Longleaf pine
Pitch pine
Pond pine
Sand pine
Shortleaf pine
Slash pine
Spruce pine
Table-Mt. pine
Virginia pine

OTHER SOFTWOODS

Atlantic white-cedar
Baldcypress
Fir
Hemlock
Northern white-cedar
Pondcypress
Redcedar
Spruce
White pine

SOFT HARDWOODS

Basswood
Black cherry
Blackgum (lowland)
Blackgum (upland)
Boxelder
Buckeye
Butternut
Cottonwood
Cucumbertree
Elm
Hackberry
Loblolly-bay
Magnolia
Red maple
Silverbell (in mts.)
Silver maple
Sweetbay
Sweetgum
Sycamore
Water tupelo
Willow
Yellow-poplar

HARD HARDWOODS

Ash
Beech
Birch (except yellow)
Black locust
Black oak
Black walnut
Bur oak
Cherrybark oak
Chestnut oak
Chinkapin oak
Dogwood
Florida maple
Hickory
Holly
Honeylocust
Laurel oak
Live oak
Mulberry
Overcup oak
Persimmon (forest grown)
Pin oak
Post oak
Northern red oak
Scarlet oak
Shingle oak
Shumard oak
Southern red oak
Sugar maple
Swamp chestnut oak
Swamp white oak
Water oak
White oak
Willow oak
Yellow birch

MISCELLANEOUS

Bear oak
Blackjack oak
Bluejack oak
Dwarf live oak
Dwarf post oak
Turkey oak
Other scrub oaks
Ailanthus
American mt. ash
Blue beech
Catalpa
Chalk maple
Chestnut
Chinaberry
Domestic fruit (apple, etc.)
Fire cherry
Eastern hophornbeam
Mountain maple
Ogeechee gum
Osage-orange
Persimmon (field grown)
Planertree (water elm)
Redbay
Redbud
Royal paulownia
Sassafras
Serviceberry
Silverbell (except mts.)
Sourwood
Striped maple
Other miscellaneous trees

VOLUME DISTRIBUTION

Tree size Bolts (8')	Tree size Logs (16')	Bolt number 1	2	3	4	5	6	7	8	9	10
		-------Percent of tree volume----------									
2	1	56	44								
3	1½	41	33	26							
4	2	33	28	22	17						
5	2½	27	23	19	17	14					
6	3	24	21	18	15	12	10				
-	3½	22	19	17	14	12	9	7			
-	4	20	18	15	13	11	9	8	6		
-	5	18	15	13	12	10	9	8	6	5	3

PRIMARY PAST TREATMENT OR DISTURBANCE

00	No treatment or disturbance
01	Harvesting followed by artificial regeneration
02	Harvesting followed by natural regeneration } not seed tree
03	Harvesting without regeneration } not seed tree
04	Commercial thinning
05	Precommercial thinning
06	Cleaning, release, or other intermediate cutting
07	Clearing or other site preparation
08	Girdling or poisoning of undesirable trees
09	Prescribed burning
10	Major drainage efforts
11	Removal of selected trees resulting in high grading
12	Significant damage from wildfire
13	Major man-caused flooding
14	Grazing or other activity that retards or precludes development of understory
15	Turpentining
16	Artificial regeneration after site preparation
17	Artificial regeneration without site preparation
18	Construction of fences, woods roads, fire breaks, trash pits, etc., if such activity has significantly influenced the stand condition
19	Natural regeneration on nonforest land (Sample kind 1 only)
20	Artificial regeneration on nonforest land (Sample kind 1 only)
21	Harvesting leaving seed trees, with satisfactory regeneration
22	Harvesting leaving seed trees without satisfactory regeneration
23	Salvage cut
24	Significant damage from disease
25	Significant damage from insects
26	Significant damage from weather or other natural destructive agents
99	Other (specify in item 107 under notes)

SECONDARY AND TERTIARY PAST TREATMENT OR DISTURBANCE AND OLD PAST DISTURBANCE CLASSIFICATION

0	None
1	Timber cutting
2	Mechanical site preparation
3	Drainage
4	Prescribed fire
5	Grazing
6	Weather
7	Insects
8	Disease
9	Other

PHYSIOGRAPHIC CLASS

11	High mountain tops and slopes
12	Sand dunes and sand ridges
13	Low mountain tops and dry slopes
14	Sand hills
15	Mountain foothills
19	Other xeric
21	Flatwoods and dry pocosins
22	Rolling uplands
23	Bluffs
24	Mountain saddles and moist slopes
25	Natural stream levees
26	Valley bottoms
27	Mountain coves
28	Narrow stream margins
29	Broad stream margins
29	Other mesic
31	Deep swamps
32	Cypress strands
33	Small drains
34	Cypress ponds
35	Willow heads and strands
36	Bays and wet pocosins
37	Marl flats and forest prairies
39	Other hydric

TROPICALS

984	Australian pine
982	Cajeput-tree
986	Carribean pine
985	Citrus
510	Eucalyptus
940	Mahogany
983	Silk oak
006	Other tropicals
911	Sable palm
910	Other palms

TABLE OF VARIABLE PLOT LIMITING DISTANCE [illegible]

Slope 0

DBH	Tenths of I[illegible] 0	1	2	3	4	5	6	7	8	9
	------------------ Distance in feet ------------------									
05	07.10	07.24	07.38	07.53	07.67	07.81	07.95	08.09	[illegible]	08.38
06	08.52	08.66	08.80	08.95	[illegible]	[illegible]	[illegible]	09.51	[illegible]	[illegible]
07	[illegible]	[illegible]	10.22	10.37	10.51	[illegible]	[illegible]	10.93	[illegible]	11.22
08	11.36	[illegible]	11.64	11.79	11.93	12.07	12.21	[illegible]	12.50	12.64
09	12.78	12.92	13.06	13.21	13.35	13.49	13.63	13.77	13.92	14.06
10	14.20	14.34	14.48	14.63	14.77	14.91	15.05	15.20	15.34	15.48
11	15.62	15.76	15.91	16.05	16.19	16.33	16.47	16.62	16.76	16.90
12	17.04	17.18	17.32	17.47	17.61	17.75	17.89	18.04	18.18	18.32
13	18.46	18.60	18.75	18.89	19.03	19.17	19.31	19.46	[illegible]	19.74
14	19.88	20.02	20.17	20.31	20.45	20.59	20.73	20.88	[illegible]	21.16
15	21.30	21.44	21.59	21.73	21.87	22.01	22.15	[illegible]	22.44	22.58
16	22.72	22.86	23.01	23.15	23.29	23.43	23.5	23.72	[illegible]	[illegible]
17	24.14	24.28	24.43	24.57	24.71	24.85	24.99	25.14	25.28	25.42
18	25.56	25.70	25.85	25.99	26.13	[illegible]	26.41	26.56	26.70	26.84
19	26.98	27.12	27.27	27.41	27.55	27.69	27.83	27.98	28.12	28.26
20	28.40	28.54	28.69	28.83	28.97	29.11	[illegible]	[illegible]	29.54	[illegible]
21	29.82	29.96	30.11	30.25	30.39	30.53	30.67	30.82	30.96	31.10
22	31.24	31.38	31.53	31.67	31.81	31.95	32.09	32.24	32.38	32.52
23	32.66	32.80	32.95	33.09	33.23	33.37	33.51	33.66	33.80	33.94
24	34.08	34.22	34.37	34.51	34.65	34.79	34.93	35.08	35.22	35.36
25	35.50	35.64	35.79	35.93	36.07	36.21	36.35	36.50	36.64	36.78
26	36.92	37.06	37.21	37.35	37.49	37.63	37.77	37.92	38.06	38.20
27	38.34	38.48	38.63	38.77	38.91	39.05	39.19	39.34	39.48	39.62
28	39.76	39.90	40.05	40.19	40.33	40.47	40.61	40.76	[illegible]	41.04
29	41.18	41.32	41.47	41.61	41.75	41.89	42.03	42.18	42.32	42.46
30	42.60	42.74	42.89	43.03	43.17	43.31	43.45	43.60	43.74	43.88
31	44.02	44.16	44.31	44.45	44.59	44.73	44.87	[illegible]	45.16	45.30
32	45.44	45.59	45.73	45.87	46.01	46.15	46.30	46.44	46.58	46.72
33	46.86	47.01	47.15	47.29	47.43	47.57	47.72	[illegible]	48.00	48.14
34	48.28	48.43	48.57	48.71	48.85	[illegible]	49.14	[illegible]	49.42	49.56
35	49.70	49.85	49.99	50.13	50.27	50.41	50.56	[illegible]	50.84	50.98
36	51.12	51.27	51.41	[illegible]	[illegible]	51.83	[illegible]	52.12	52.26	52.40
37	52.54	52.69	52.83	52.97	53.11	[illegible]	53.40	53.54	53.68	[illegible]
38	53.96	54.11	54.25	54.39	54.53	54.67	[illegible]	[illegible]	[illegible]	55.24
39	55.38	55.53	55.67	55.81	[illegible]	56.09	56.24	56.38	56.52	[illegible]
40	56.80	56.95	[illegible]	57.23	57.37	57.51	57.66	[illegible]	57.94	58.08

DAMAGE CODES

00	No damage
10	Insects
20	Other disease
21	Fusiform rust
22	Annosus root rot
23	Littleleaf disease
24	Blister rust
25	Hardwood cankers
26	Branch stubs } 5% cull
27	Top breakage } 5% cull
28	Other basal defects } 5% cull
30	Fire
40	Animal
50	Weather
60	Suppression and stagnation
80	Logging and related
84	Turpentining
90	Form (damaging)
	Saplings only
91	Form (culling)
92	Off site (damaging)
93	Off site (culling)

UTILIZATION

Product known

1	Tree not used
2	Tree bucked for product in place
3	Tree length logging

Product estimated

4	Tree not used
5	Tree bucked for product in place
6	Tree length logging

CAUSE OF DEATH

Timber cut		Mortality	
81	Logging	10	Insects
82	TSI	20	Disease
83	Turpentining	30	Fire
84	Land Clearing	40	Animals
85	Conversion to non-forest or noncommercial forest land use	50	Weather
		60	Suppression
		70	Other

PRODUCT

Primary	Secondary	
00	-0	No product
1-	-1	Sawlog
2-	-2	Veneer log or bolt
3-	-3	Cooperage log or bolt
4-	-4	Pulpwood
5-	-5	Piling
6-	-6	Poles
7-	-7	Fencepost
8-	-8	Fuelwood
9-	-9	Miscellaneous prod

TREE HISTORY

1	Live tree recorded on previous survey or live tree tallied on the 10-point cluster
2	Ingrowth 1.0 inch d.b.h. or larger on smallest fixed plot not recorded on previous survey
3	Live tree on variable plot not recorded on previous survey
5	Salvable dead tree 5.0 inches d.b.h. or larger recorded as a live tree on previous survey
6	Nonsalvable dead tree 1.0 inches d.b.h. or larger recorded as a live tree on previous survey (includes salvable 1.0-4.9 inches)
7	Mortality tree 5.0 inches d.b.h. or larger on the smallest fixed plot not recorded as a live tree on the previous survey (Mortality tree less than 1.0 inches during last survey and now 5.0 inches or larger)
8	Tree removed from commercial forest recorded as live tree on previous survey
9	Tree removed from commercial forest 5.0 inches d.b.h. or larger on the smallest fixed plot not recorded as a live tree on the previous survey (Timber removals less the 1.0 inches during last survey and now 5.0 inches or larger)
[illegible]	Stump of dead tree 1.0 inch d.b.h. or larger recorded as a live tree on previous survey and harvested for a product

FOREST TYPE

24	White pine-hemlock
10	Spruce-fir
21	Longleaf pine
22	Slash pine
31	Loblolly pine
32	Shortleaf pine
33	Virginia pine
34	Sand pine
35	Redcedar
36	Pond pine
37	Spruce pine
38	Pitch pine
39	Table-mt. pine
53	Oak-hickory
52	Chestnut oak
57	Southern scrub oak
60	Oak-gum-cypress
70	Elm-ash-cottonwood
80	Maple-beech-birch

PROSPECTIVE DEN TREES

0	No damage
1	Basal defect
2	Top breakage
3	Branch stubs
4	Basal defect and top breakage
5	Basal defect and branch stubs
6	Top breakage and branch stubs
7	Basal defect, top breakage and branch stubs

CODING SUMMARY, PART I
SOUTH CAROLINA
MARCH 1977

[illegible]

[illegible]	[illegible] (radius in feet)	[illegible] (side in feet)
[illegible] Acre	[illegible]	[illegible]
1/2 Acre	83.26	[illegible]
[illegible]	[illegible]	93.34

[illegible]

Primary	Secondary	
	[illegible]	[illegible]
2-	[illegible]	[illegible]
3-	[illegible]	[illegible] & [illegible]
[illegible]		Nonstocked

[illegible]

[illegible] [illegible]

[illegible] [illegible]

[illegible] [illegible]

[illegible] [illegible] forest between [illegible] and [illegible] acres and bounded on all sides by nonforest uses

4 [illegible] forest between [illegible] and 200 acres and bounded on all sides by nonforest uses

[illegible] A long, narrow stringer or strip of forest bounded on both sides by nonforest uses

[illegible] Many small, scattered, irregular-shaped forest areas [illegible] by stringers or strips with interspersed nonforest

[illegible] Intermixed forest and nonforest of about the same sizes and shapes

[illegible] [illegible] areas of forest land

[illegible] [illegible] areas of over [illegible] acres

[illegible]

[illegible]

[illegible]	Feet [illegible]	Percent Slope	Feet added
[illegible]	0.1	[illegible]	0.1
[illegible]	0.4	10	0.5
[illegible]	0.8	[illegible]	1.1
20	1.4	[illegible]	2.0
[illegible]	2.1	25	3.0
[illegible]	[illegible]	30	4.2
[illegible]	[illegible]	35	5.6
40	5.0	40	7.2
45	6.2	45	[illegible]
50	7.4	[illegible]	10.6
[illegible]	[illegible]	[illegible]	12.4
[illegible]	9.9	60	14.[illegible]
[illegible]	11.3	65	16.2
70	12.7	70	18.1
[illegible]	15.3	[illegible]	21.9
[illegible]	17.9	[illegible]	25.6
100	[illegible]	100	29.3
[illegible]	23.0	[illegible]	32.8
[illegible]	25.2	120	36.0

TREATMENT OPPORTUNITY

[illegible] No treatment needed

[illegible] [illegible]

[illegible] [illegible]

[illegible] [illegible]

4 [illegible]

[illegible] [illegible], release, or other [illegible] cutting

[illegible] Stand conversion

[illegible] Artificial regeneration without site preparation

[illegible] Artificial regeneration after site preparation

NUMBER OF TREES REQUIRED FOR 10[illegible]-PERCENT STOCKING BY D.B.H. CLASS

[illegible] class	[illegible] Acre	[illegible] Acre
[illegible]	[illegible]4	4[illegible]
1[illegible]4	[illegible]	[illegible]
[illegible]	5[illegible]	2[illegible]
[illegible]	4[illegible]	2[illegible]
[illegible]	[illegible]	1[illegible]
[illegible]	1[illegible]	1[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	5
[illegible]	[illegible]	[illegible]

[illegible] 4 [illegible] occuring in clumps should [illegible]

STOCKING STANDARDS FOR TREES

Tree size	1 Acre No trees full stocking	 Percent per tree
[illegible]	[illegible]	.17
2	560	.18
4	460	.22
[illegible]	34[illegible]	.29
8	240	.4[illegible]
1[illegible]	155	.65
12	115	.87
14	90	1.11
16	72	1.39
1[illegible]	60	1.67
[illegible]+	51	1.96

SEED SOURCE

[illegible] No seed source

1 Yellow pine

[illegible] Other softwood

3 Desirable hardwood seed trees (sweetgum, yellow-poplar, water tupelo, lowland blackgum, cherrybark oak, northern red oak, white oak, [illegible] chestnut oak, sycamore, or ash)

4 Other hardwood seed tree species

MANAGEMENT TREE CLASS

1 A tree, part of the manageable stand

2 A tree, competing with or in conflict with manageable stand trees

3 A miscellaneous tree immaterial to the manageable stand trees

ACCESSIBILITY

[illegible] The forest condition is highly accessible using existing roads

[illegible] Roads could be easily built into the area.

[illegible] Roads would be difficult to build into the area.

4 Roads would be very difficult or impractical to build into the area [illegible], water, or other physical obstacles.

OPERABILITY

1 No problem

[illegible] Limited to seasonal use due to water [illegible]

3 Moderate slopes (averaging [illegible] percent), irregular terrain, or other ground conditions limiting the type of equipment that could be operated within the forest condition

4 Mixed wet and dry areas within forest [illegible] channeled streams with intermixed dry [illegible]

[illegible] Severe slopes (averaging 40-49 percent), broken terrain, or other adverse ground conditions which drastically limit equipment use.

6 Adverse operating conditions caused by year round water problems

7 Slopes of 50 percent or more.

INHIBITING VEGETATION CLASS

[illegible] No significant inhibiting vegetation

[illegible] Scattered, small stems, and low heights

[illegible] Scattered, with either large stems or tall heights

3 Scattered, with large stems and tall heights

4 Intermediate density, small stems, and low heights

5 Intermediate density, with either large stems or tall heights

6 Intermediate density, with large stems and tall heights

7 Dense with small stems and low heights

[illegible] Dense with either large stems or tall heights

[illegible] Dense with large stems and tall heights

SLOPE (Percent)

0	0-9
[illegible]	1[illegible]-[illegible]
2	20-29
3	30-39
4	40-4[illegible]
5	5[illegible]-5[illegible]
6	6[illegible]-[illegible]9
7	70-79
8	80-89
[illegible]	[illegible]+

ASPECT (Degrees)

[illegible]	No aspect
[illegible]	338-22
[illegible]	23-67
3	68-112
4	113-157
[illegible]	158-[illegible]02
6	203-247
7	248-292
8	[illegible]

SECTION IDENT.

[illegible] Stump section

1 Saw log section, main stem

[illegible] Upper stem section, main stem

3 Top section, main stem

4 Saw log section, fork

5 Upper stem section, fork

6 Top section, fork

7 Utilizable limb section

8 Top section, utilizable limb

9 Minor limbs

CROWN RATIO

(percent of live crown)

[illegible]	0-[illegible]
[illegible]	10-1[illegible]
[illegible]	[illegible]
4	[illegible]
[illegible]	4[illegible]-4[illegible]
[illegible]	5[illegible]-5[illegible]
[illegible]	6[illegible]-[illegible]
[illegible]	[illegible]-79
[illegible]	[illegible]
[illegible]	[illegible]

CROWN CLASS

1 Open grown

2 Dominant

3 Codominant

4 Intermediate

5 Overtopped

LIVE TREE CAVITIES

Location (left digit)

[illegible] None

1 Cavities below d.b.h.

2 Cavities above d.b.h.

3 Cavities below and above d.b.h.

Number (right digit)

X(1-9)

POINT HISTORY

1 Point remeasured and new inven[illegible] taken at same point without s[illegible] or substituting

[illegible] Point remeasured at original location but inventory taken a shifted location

3 Point remeasured at original location [illegible] inventory taken a substitute point (points 2

SAMPLE KIND

1 Sample location center did n[illegible] qualify as unreserved commer[illegible] forest land at time of last [illegible]

[illegible] Sample location center qual[illegible] unreserved commercial fores[illegible] at time of last survey and [illegible] struction of old plot is po[illegible]

3 Sample location center qual[illegible] as unreserved commercial fo[illegible] land at time of last survey reconstruction of old plot impossible

NUMBER OF WELL-[illegible] TR[illegible] ACRE [illegible]

D.B.H. (inches)	[illegible]
[illegible]	[illegible]
1[illegible]	1[illegible]
11	1[illegible]
1[illegible]	1[illegible]
1[illegible]	1[illegible]
14	[illegible]
1[illegible]	[illegible]
1[illegible]	[illegible]
17-18	[illegible]
19-20	[illegible]
20+	4

GROUND LAND USE

[illegible]	Commercial forest
4	Unproductive forest
5[illegible]	Prod. forest reserve[illegible]
61	Cropland
62	Improved pasture
[illegible]	Natural rangeland
64	Idle farmland
66	Other farmland, incl[illegible] farmsteads
[illegible]7	Urban and other
[illegible]	Marsh
91	Census water
92	Non-census water

OWNER CLASS

11	National Forest
1[illegible]	BLM
1[illegible]	Indian
1[illegible]	Miscel. federal
[illegible]	State
1[illegible]	County and municipal
[illegible]	Forest industry
4[illegible]	Farmer
5[illegible]	Farmer-owned leased
6[illegible]	Miscel. priv., corporate
7[illegible]	Miscel. priv., individua[illegible]
8[illegible]	Miscel. priv., corporate
90	Miscel. priv., individua[illegible]

SHAPE OF FOREST CONDITION

1 A regular shaped area having customary width-to-length re[illegible]ship and a normal boundary.

[illegible] A central area having one or protrusions, extensions, or [illegible] boundary. Sample location is [illegible] central area.

3 A central area having one or protrusions, extensions, or [illegible] boundary. Sample location is [illegible] the central area

4 Two or more distinct areas l[illegible] linked together by strips, s[illegible] or bands of similar forest c[illegible] Sample location is in the di[illegible] area.

5 Two or more distinct areas l[illegible] linked together by strips, s[illegible] or bands of similar forest c[illegible] Sample location is not in th[illegible] distinct area

[illegible] Strips, stringers, or bands [illegible] land typical of long narrow [illegible] margins, narrow cypress stra[illegible] long bands of reverted land.

TREE CLASS

1 Desirable tree

2 Acceptable tree

3 Rough tree

4 Rotten tree

CODING SUMMARY,
SOUTH CAROLINA
MARCH 1977

OMMON NAME

ELLOW PINES

oblolly pine
ongleaf pine
itch pine
ond pine
and pine
hortleaf pine
lash pine
pruce pine
able-Mt. pine
irginia pine

THER SOFTWOODS

tlantic white-cedar
aldcypress
ir
emlock
orthern white-cedar
ondcypress
dcedar
pruce
ite pine

PT HARDWOODS

sswood
ack cherry
ackgum (lowland)
ackgum (upland)
xelder
ckeye
tternut
ttonwood
cumbertree
m
ckberry
blolly-bay
gnolia
d maple
lverbell (in mts.)
lver maple
eetbay
eetgum
camore
ter tupelo
llow
llow-poplar

RD HARDWOODS

n
ech
rch (except yellow)
ack locust
ack oak
ack walnut
oak
rrybark oak
stnut oak
nkapin oak
gwood
rida maple
kory
ly
eylocust
rel oak
e oak
berry
rcup oak
simmon (forest grown)
oak
t oak
thern red oak
rlet oak
ngle oak
mard oak
thern red oak
ar maple
mp chestnut oak
mp white oak
er oak
te oak
low oak
low birch

SCELLANEOUS

ar oak
ackjack oak
ejack oak
arf live oak
arf post oak
rkey oak
her scrub oaks
lanthus
erican mt. ash
e beech
talpa
alk maple
estnut
inaberry
mestic fruit (apple, etc.)
e cherry
stern hophornbeam
untain maple
eechee gum
age-orange
rsimmon (field grown)
nertree (water elm)
lbay
lbud
yal paulownia
ssafras
rviceberry
verbell (except mts.)
rwood
riped maple
her miscellaneous trees

TROPICALS

984	Australian pine
982	Cajeput-tree
986	Carribean pine
985	Citrus
510	Eucalyptus
940	Mahogany
983	Silk oak
006	Other tropicals
911	Sable palm
910	Other palms

CODE	COMMON NAME
	SHRUBS
007	Alder
008	Azalea
009	Bayberry
023	Blackberry
024	Blueberry
026	Bluestem palmetto
027	Brambles
028	Buffalo-nut
029	Chinkapin
032	Devil's-walking-stick
033	Elderberry
034	Gallberry
035	Fetterbush
036	Haw
038	Hawthorn
039	Hazel
044	Horse-sugar
045	Huckleberry
046	Hydrangea
047	Laurel
048	Mangrove
087	Mistletoe
049	Pawpaw
052	Plum
166	Privet
053	Rhododendron
054	Rose
055	Saw-palmetto
056	Spicebush
163	St. Johnswort
057	Strawberry bush
058	Sumac
059	Titi
069	Viburnum
074	Waxmyrtle
075	Witch-hazel
076	Yaupon
077	Other shrubs
	VINES
079	Climbing rose
08[illegible]	Crossvine
083	Dewberry
084	Greenbrier
085	Honeysuckle
086	Kudzu
088	Poison ivy
089	Rattan
[illegible]	Trumpet creeper
133	Virginia creeper
134	Wild grape
135	Yellow jessamine
136	Other vines
	GRASSES AND GRASSLIKES
137	Bahiagrass and other pasture grasses
138	Bluestem, big
139	Bluestem, broomsedge
140	Bluestem, slender
141	Bluestem, creeping
164	Bluestem, little
142	Bristle grass
143	Carpetgrass
144	Cutover muhly
145	Fescue
167	Indiangrass
146	Marsh-grass
147	Panicums
148	Paspalum
149	Reeds
168	Sawgrass
151	Sedges
152	Switchcane
153	Threeawn, wiregrass
154	Uniolas
155	Other grasses
156	Other grasslikes
	FORBS AND OTHERS
157	Cactus
158	Composites
159	Ferns
161	Legumes
162	Lichens
165	Other forbs
169	Moss

BROAD SPECIES CLASSES

1	Yellow pines
2	Other softwoods
3	Hardwoods (scrub oaks & misc.)
4	Tropicals
5	Shrubs
6	Vines
7	Grasses and grasslikes
8	Forbs & others

BROWSING

0	No browsing
1	Light browsing - difficult to find browse plants on sample. Less than 5 percent of plants grazed.
2	Moderate browsing - frequently find browsing on sample acre
3	Heavy browsing - generally more than 35 percent of plants on the sample acre browsed

MILL RESIDUES

0	None
1	Sawdust piles, slabs, edgings, sawmill structure, or other mill residues

LOGGING SLASH

0	None
1	Logging slash, windthrown trees or broken tops

LITTER AND TRASH

0	None
1	Trash piles, abandoned autos, dumps etc.

GULLIES, RAVINES AND DITCHES

0	None
1	Gullies, ravines or ditches present

HOLES AND CAVES

0	None
1	Holes, burrows, crevices or caves present

ROCK OUTCROPS, ROCK SLIDES AND GRAVEL BEDS

0	None
1	Rock outcrops, rock slides or gravel beds

MARSH CONDITION

0	None
1	Small areas of marsh-like conditions or moist seepages occurring within the forest

SPANISH MOSS

0	None
1	One or more trees in the forest condition contains Spanish Moss

WATER TYPE

0	None
1	Permanent
2	Temporary

HIKING

0	None
1	Foot trails, trail markers, or blazed trees

HUNTING

0	None
1	Spent shotgun shells, tree stands or other signs of hunting

GRAZING INTENSITY

0	None
1	Light grazing - difficult to find grazed plants. Less than 35 % of plants grazed.
2	Moderate grazing - frequently find grazing on the sample acre. Generally 35 to 70 % of plants are grazed.
3	Heavy grazing - extensive

LIVESTOCK FENCING

0	Not fenced, or inadequate fencing for grazing use
1	Adequate fencing for grazing use

PEOPLE USE

0	No evidence of people use
1	Occasional use
2	Moderate use
3	Intensive use

CAMPING

0	None
1	Campsites, litter or miscellaneous tree cutting

FISHING

0	None
1	Paths along stream bank or lake, bait containers or posted fishing regulations

TRAIL BIKES

0	None
1	Tire impressions in forest condition sampled

OTHER USE

0	None
1	Other significant use of the forest condition

POSTED

0	None
1	Locked gate
2	Keep out
3	No trespassing
4	No hunting
5	No fishing
6	No dumping
7	Other posted signs
8	Owner contact
9	Other evidence

TRAILS

0	None
1	Improved trail
2	Active woods road
3	Unimproved trail
4	Old woods road (include tram roads)
5	Skid trail
6	Game or livestock trail
7	Other road or trail

BURN HISTORY

0	None
1	Burned within past year
2	Burned within past 1-3 years
3	Burned within past 3-10 years
4	Burned beyond 10 years

SEASON OF THE YEAR

1	Growing season
2	Dormant season

SOIL TEXTURE

1	Sands
2	Sandy loams
3	Loams
4	Clay loams
5	Clays

SLOPE LENGTH OR DISTANCE TO WATER IN FEET FROM SAMPLE CENTER

0	No obstruction, no slope, or plot center in primary water
1	1 - 99
2	100 - 199
3	200 - 299
4	300 - 399
5	400 - 499
6	500 - 599
7	600 - 699
8	700 - 799
9	800 +

SOIL STRUCTURE

0	None
1	Blocky
2	Platy

SOIL EROSION

0	None
1	Light - very little sheet erosion
2	Medium - both sheet and rill erosion
3	High - bad rill erosion, gullies

PROXIMITY
FEET FROM SAMPLE CENTER

0	Adjacent (less than 118 feet)
1	119-150
2	151-200
3	201-250
4	251-300
5	301-400
6	401-500
7	501-600
8	601-700
9	701-833 (first circle)

LAND USE IMPACT AND PRIORITIES

1	Urban buildup
2	Lakes and seashores
3	Rivers and streams
4	Commercial-reserved forest land
5	Agricultural lands
6	Unproductive forest
7	Major highways
8	Other roads
9	Rights-of-way
0	Commercial forest

PERCENT FOREST

Percent forest	Code	Number of dot counts			
		(20 dots) 1 position	(40 dots) 2 positions	(60 dots) 3 positions	(80 dots) 4 positions
1-5	0	0-1	0-2	0-3	0-4
6-15	1	2-3	3-6	4-9	5-12
16-25	2	4-5	7-10	10-15	13-20
26-35	3	6-7	11-14	16-21	21-28
36-45	4	8-9	15-18	22-27	29-36
46-55	5	10-11	19-22	28-33	37-44
56-65	6	12-13	23-26	34-39	45-52
66-75	7	14-15	27-30	40-45	53-60
76-85	8	16-17	31-34	46-51	61-68
86-100	9	18-20	35-40	52-60	69-80

CA IVERSITY PROFILE RECORD CODING SUMMARY
A NA, PART I
97
••••• (REVISED)

PLANT SPECIES[3]

Code	Common name	Scientific name
	YELLOW PINES	
131	Loblolly pine	*Pinus taeda*
121	Longleaf pine	*Pinus palustris*
126	Pitch pine	*Pinus rigida*
128	Pond pine	*Pinus serotina*
107	Sand pine	*Pinus clausa*
110	Shortleaf pine	*Pinus echinata*
111	Slash pine	*Pinus elliottii*
115	Spruce pine	*Pinus glabra*
123	Table-Mountain pine	*Pinus pungens*
132	Virginia pine	*Pinus virginiana*
	OTHER SOFTWOOD	
043	Atlantic white-cedar	*Chamaecyparis thyoides*
221	Baldcypress	*Taxodium distichum* var. *distichum*
010	Fir	*Abies* spp.
260	Eastern hemlock	*Tsuga canadensis*
241	Northern white-cedar	*Thuja occidentalis*
222	Pondcypress	*Taxodium distichum* var. *nutans*
060	Eastern redcedar	*Juniperus virginiana*
090	Spruce	*Picea* spp.
129	Eastern white pine	*Pinus strobus*
	SOFT HARDWOODS	
950	American basswood	*Tilia americana*
762	Black cherry	*Prunus serotina*
694	Blackgum (lowland)	*Nyssa sylvatica*
693	Blackgum (upland)	*Nyssa sylvatica*
313	Boxelder	*Acer negundo*
330	Buckeye	*Aesculus* spp.
601	Butternut	*Juglans cinerea*
740	Cottonwood	*Populus* spp.
651	Cucumbertree	*Magnolia acuminata*
970	Elm	*Ulmus* spp.
460	Hackberry	*Celtis occidentalis*
555	Loblolly-bay	*Gordonia lasianthus*
652	Magnolia	*Magnolia* spp.
316	Red maple	*Acer rubrum*
580	Silverbell (in mountains)	*Halesia* spp.
317	Silver maple	*Acer saccharinum*
653	Sweetbay	*Magnolia virginiana*
611	Sweetgum	*Liquidambar styraciflua*
731	American sycamore	*Platanus occidentalis*
691	Water tupelo	*Nyssa aquatica*
920	Willow	*Salix* spp.
621	Yellow-poplar	*Liriodendron tulipifera*
	HARD HARDWOODS	
540	Ash	*Fraxinus* spp.
531	American beech	*Fagus grandifolia*
370	Birch (except yellow)	*Betula* spp.
901	Black locust	*Robinia pseudoacacia*
837	Black oak	*Quercus velutina*
602	Black walnut	*Juglans nigra*
823	Bur oak	*Quercus macrocarpa*
813	Cherrybark oak	*Quercus falcata* var. *pagodaefolia*
832	Chestnut oak	*Quercus prinus*
826	Chinkapin oak	*Quercus muehlenbergii*
491	Flowering dogwood	*Cornus florida*

311	Florida maple	*Acer barbatum*
400	Hickory	*Carya* spp.
591	American holly	*Ilex opaca*
552	Honeylocust	*Gleditsia triacanthos*
820	Laurel oak	*Quercus laurifolia*
838	Live oak	*Quercus virginiana*
680	Mulberry	*Morus* spp.
822	Overcup oak	*Quercus lyrata*
521	Common persimmon (forest grown)	*Diospyros virginiana*
830	Pin oak	*Quercus palustris*
835	Post oak	*Quercus stellata*
833	Northern red oak	*Quercus rubra*
806	Scarlet oak	*Quercus coccinea*
817	Shingle oak	*Quercus imbricaria*
834	Shumard oak	*Quercus shumardii*
812	Southern red oak	*Quercus falcata*
318	Sugar maple	*Acer saccharum*
825	Swamp chestnut oak	*Quercus michauxii*
804	Swamp white oak	*Quercus bicolor*
827	Water oak	*Quercus nigra*
802	White oak	*Quercus alba*
831	Willow oak	*Quercus phellos*
371	Yellow birch	*Betula alleghaniensis*

MISCELLANEOUS TREES

816	Bear oak	*Quercus ilicifolia*
824	Blackjack oak	*Quercus marilandica*
807	Bluejack oak	*Quercus incana*
841	Dwarf live oak	*Quercus* spp.
840	Dwarf post oak	*Quercus* spp.
819	Turkey oak	*Quercus laevis*
899	Other scrub oaks	*Quercus* spp.
341	Ailanthus	*Ailanthus* spp.
548	American mountain-ash	*Sorbus americana*
391	American hornbeam	*Carpinus caroliniana*
451	Catalpa	*Catalpa* spp.
310	Chalk maple	*Acer* spp.
421	American chestnut	*Castanea dentata*
661	Chinaberry	*Melia azedarach*
660	Domestic fruit (apple, etc.)	*Malus* spp.
760	Fire cherry	*Prunus* spp.
701	Eastern hophornbeam	*Ostrya virginiana*
319	Mountain maple	*Acer spicatum*
692	Ogeechee tupelo	*Nyssa ogeche*
641	Osage-orange	*Maclura pomifera*
521	Common persimmon (field grown)	*Diospyros virginiana*
722	Planertree (water elm)	*Planera aquatica*
721	Redbay	*Persea borbonia*
471	Eastern redbud	*Cercis canadensis*
712	Royal paulownia	*Paulownia tomentosa*
931	Sassafras	*Sassafras albidum*
352	Serviceberry	*Amelanchier* spp.
581	Carolina silverbell (except mountains)	*Halesia carolina*
711	Sourwood	*Oxydendrum arboreum*
315	Striped maple	*Acer pensylvanicum*
999	Other miscellaneous trees	————

TROPICALS

984	Casuarina	*Casuarina* spp.
982	Cajeput-tree	*Melaleuca leucadendron*
986	Caribbean pine	*Pinus caribaea*
985	Citrus	*Citrus* spp.
510	Eucalyptus	*Eucalyptus* spp.
940	Mahogany	*Swietenia* spp.
983	Silk-oak	*Grevillea robusta*

006	Other tropicals	———
911	Cabbage palmetto	*Sabal palmetto*
910	Other palms	*Sabal* spp.

SHRUBS

007	Alder	*Alnus* spp.
008	Flame azalea	*Rhododendron calendulaceum*
009	Northern bayberry	*Myrica pensylvanica*
023	Blackberry	*Rubus* spp.
024	Blueberry	*Vaccinium* spp.
026	Bluestem palmetto	*Sabal minor*
027	Brambles	*Rubus* spp.
028	Buffalo-nut	*Pyrularia pubera*
029	Chinkapin	*Castanea* spp.
032	Devil's-walkingstick	*Aralia spinosa*
033	Elderberry	*Sambucus* spp.
034	Gallberry	*Ilex* spp.
035	Fetterbush	*Lyonia lucida*
036	Haw	*Ilex* spp.
038	Hawthorn	*Crataegus* spp.
039	Hazel	*Corylus* spp.
044	Common sweetleaf	*Symplocos tinctoria*
045	Huckleberry	*Gaylussacia* spp.
046	Hydrangea	*Hydrangea* spp.
047	Mountain-laurel	*Kalmia latifolia*
048	Mangrove	*Rhizophora* spp.
087	Mistletoe	*Phoradendron* spp.
049	Pawpaw	*Asimina* spp.
052	Plum	*Prunus* spp.
166	Privet	*Ligustrum* spp.
053	Rosebay rhododendron	*Rhododendron maximum*
054	Rose	*Rosa* spp.
055	Saw-palmetto	*Serenoa repens*
056	Spicebush	*Lindera benzoin*
163	St. Johnswort	*Hypericum* spp.
057	Strawberry bush	*Euonymus americanus*
058	Sumac	*Rhus* spp.
059	Swamp cyrilla	*Cyrilla racemiflora*
069	Viburnum	*Viburnum* spp.
074	Southern bayberry	*Myrica cerifera*
075	Witch-hazel	*Hamamelis virginiana*
076	Yaupon	*Ilex vomitoria*
077	Other shrubs	———

VINES

079	Climbing rose	*Rosa* spp.
082	Crossvine	*Bignonia capreolata*
083	Dewberry	*Rubus* spp.
084	Greenbrier	*Smilax* spp.
085	Japanese honeysuckle	*Lonicera japonica*
086	Kudzu	*Pueraria lobata*
088	Poison ivy	*Rhus radicans*
089	Rataan	*Berchernia* spp.
099	Trumpet creeper	*Campsis radicans*
133	Virginia creeper	*Parthenocissus quinquefolia*
134	Summer grape	*Vitis aestivalis*
135	Yellow jessamine	*Gelsemium sempervirens*
136	Other vines	———

GRASSES AND GRASSLIKES

137	Bahiagrass (& other pasture grasses)	*Paspalum notatum*
138	Bluestem, big	*Andropogon gerardi*
139	Bluestem, broomsedge	*Andropogon virginicus*
140	Bluestem, slender	*Andropogon tener*
141	Bluestem, creeping	*Andropogon stolonifer*

164	Bluestem, little	*Andropogon scoparius*
142	Bristlegrass	*Setaria* spp.
143	Carpetgrass	*Axonopus* spp.
144	Cutover muhly	*Muhlenbergia expansa*
145	Fescue	*Festuca* spp.
167	Indian grass	*Sorghastrum* spp.
146	Marsh-grass	*Spartina* spp.
147	Panicums	*Panicum* spp.
148	Paspalum	*Paspalum* spp.
149	Common reed	*Phragmites communis*
168	Saw-grass	*Cladium jamaicense*
151	Sedges	*Cyperus* spp.
152	Switch-cane	*Arundinaria tecta*
153	Pineland three awn (wiregrass)	*Aristida stricta*
154	Uniolas	*Uniola* spp.
155	Other grasses	———
156	Other grasslikes	———

FORBS AND OTHERS

157	Cactus	*Opuntia* spp.
158	Composites	*Compositae*
159	Ferns	*Pteridophyta*
161	Legumes	———
162	Lichens	———
165	Forbs	———
169	Mosses	———

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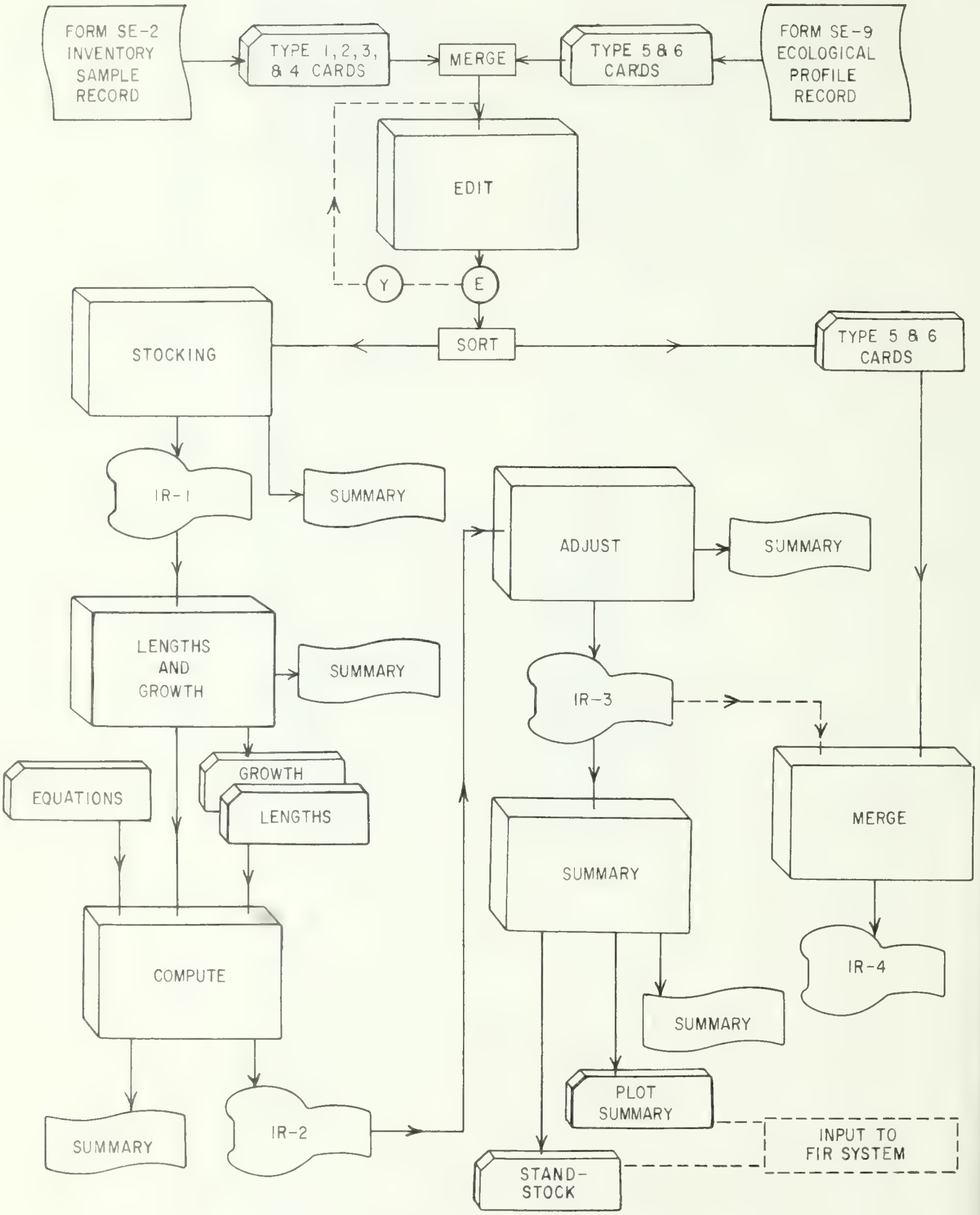
[3] Common and scientific names listed according to the following sources: Dean, Blanche Evans. 1968. Trees and shrubs in the heart of Dixie. 246 p. South. Univ. Press, Birmingham, Ala.; Fernald, Merritt Lyndon. 1950. Gray's manual of botany, 8th ed., rewritten and expanded. 1,632 p. Am. Book Co., New York; Kelsey, Harland P., and William A. Dayton. 1942. Standardized plant names. 2d ed., rev. 675 p. J. Horace McFarland Co., Harrisburg, Pa.; Little, Elbert L., Jr. 1953. Check list of native and naturalized trees of the United States (including Alaska). U.S. Dep. Agric. For. Serv., Agric. Handb. 41, 472 p. U.S. Gov. Print. Off., Washington, D.C.; U.S. Department of Agriculture, Forest Service. 1967. Forest Survey handbook. FSH 4813.1. U.S. Dep. Agric., For. Serv., Washington, D. C.; and U.S. Department of Agriculture, Soil Conservation Service. 1965. Important native grasses for range conservation in Florida. 163 p. U.S. Dep. Agric., Soil Conser. Serv., Gainesville, Fla.

INVENTORY PROCESSING SYSTEM



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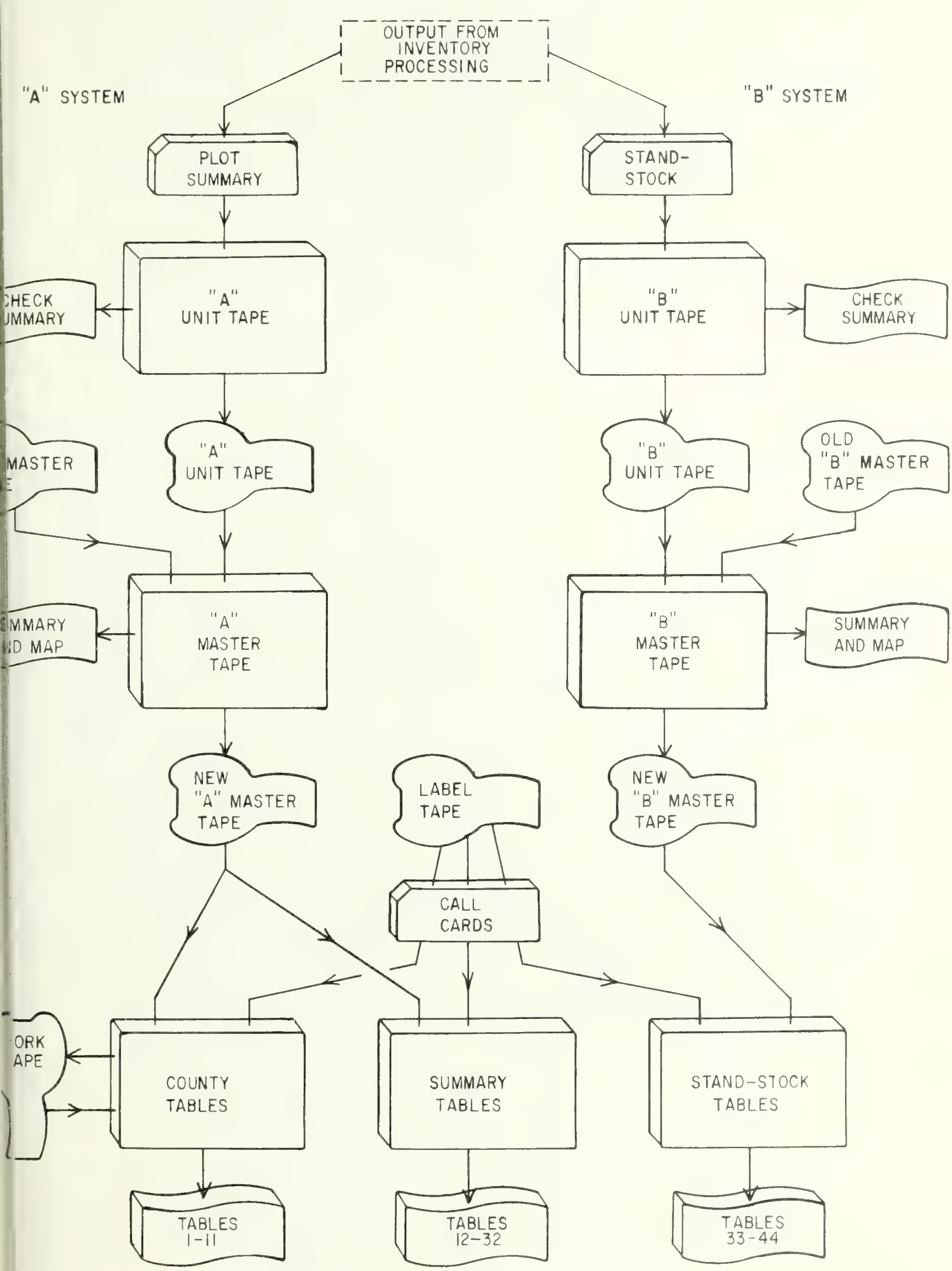

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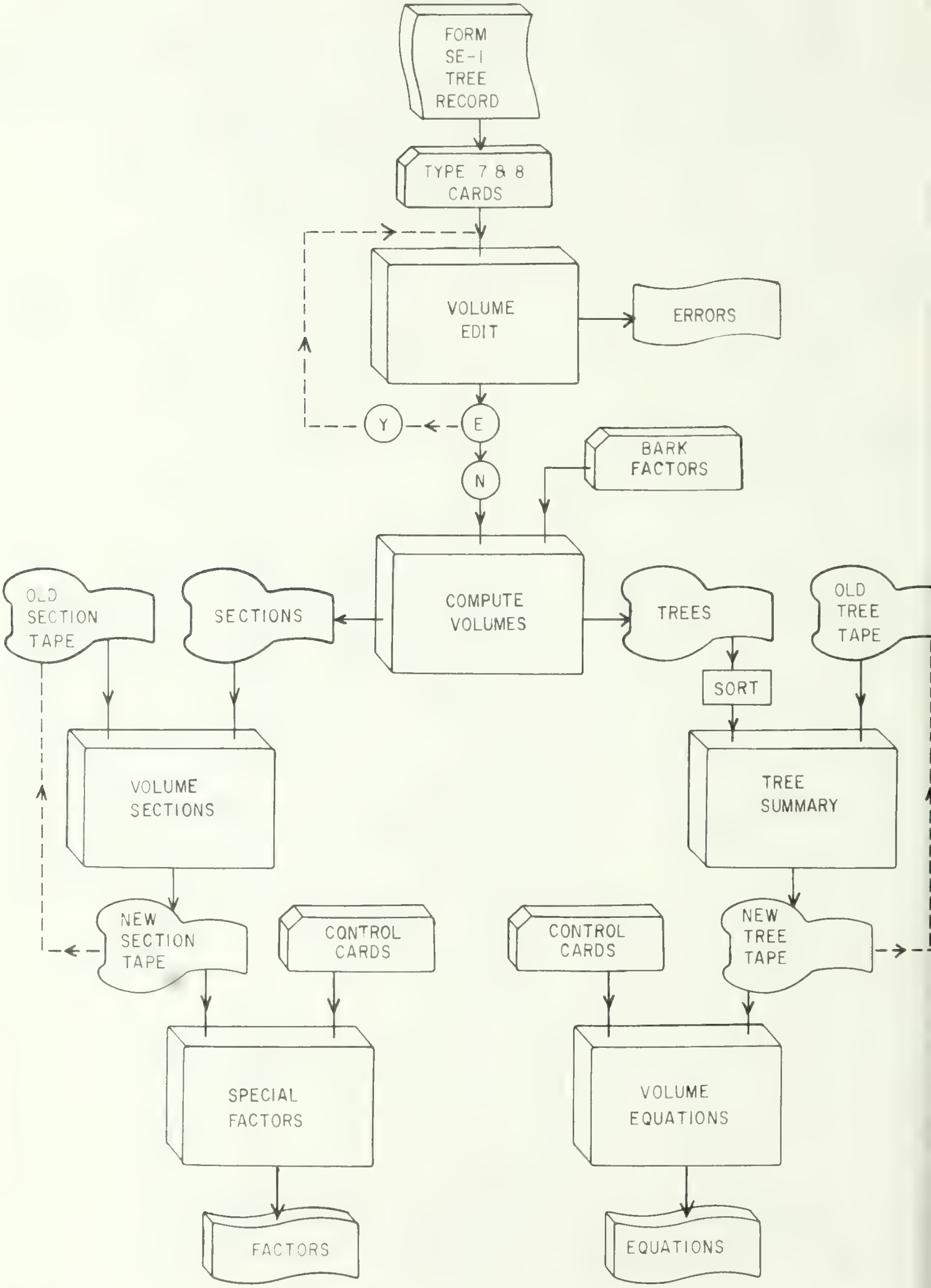

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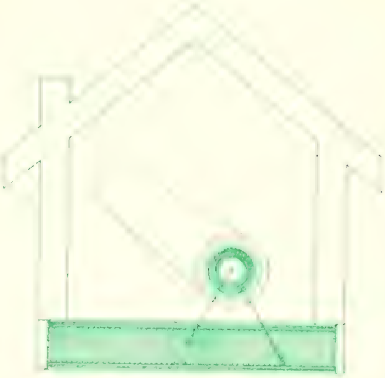

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REPORT 14

PERFORMANCE STANDARDS FOR COM-PLY FLOOR JOISTS

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November 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

PERFORMANCE STANDARDS FOR COM-PLY FLOOR JOISTS

by

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Cooperative Research by
U.S. Department of Agriculture, Forest Service
Southeastern Forest Experiment Station
and
U.S. Department of Housing and Urban Development
Division of Energy, Building Technology
and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing was initially limited to COM-PLY studs but has now been extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The Forest Service of the U.S. Department of Agriculture and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of COM-PLY studs and joists is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall and floor framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs and joists. Other reports will describe the overall project, compare the strength of composite and solid wood lumber, suggest performance standards for composite lumber, and provide construction details on houses incorporating such lumber. Still others will explore the economic feasibility of manufacturing composite lumber and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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PERFORMANCE STANDARDS FOR COM-PLY FLOOR JOISTS

Abstract.--This report presents standards for evaluating the strength, stiffness, durability, and dimensional stability of COM-PLY floor joists. The standards set levels of acceptable performance for joists used in residential construction. Test methods for evaluating performance are described in detail. Manufacturers can use these standards to determine whether COM-PLY floor joists they produce are adequate for use in building homes. Building code officials can use these standards for accepting or rejecting COM-PLY floor joists for use within the code jurisdiction.

KEYWORDS: Floor joist performance, floor joist strength, floor joist stiffness, floor performance, floor framing.

The U.S. Department of Housing and Urban Development and the Forest Service, U.S. Department of Agriculture, have performed cooperative research that has led to the development of a new composite lumber product. The new product, called COM-PLY, has potential for significantly increasing the supply of lumber for building homes. Composite lumber requires fewer trees to produce the same amount of lumber than does conventional sawing practice. The first segment of this work has developed COM-PLY studs for use in exterior walls and partitions of single-family homes, apartments, and light-frame construction.

COM-PLY lumber, including COM-PLY studs and floor joists, is a structural sandwich construction with a particleboard core placed between layers of solid wood veneer. This report deals with COM-PLY floor joists used to frame floors of single-family homes, apartments, and light-frame construction (fig. 1). These floor joists are intended to be used as substitutes for those of sawn lumber and as a complete floor framing system.

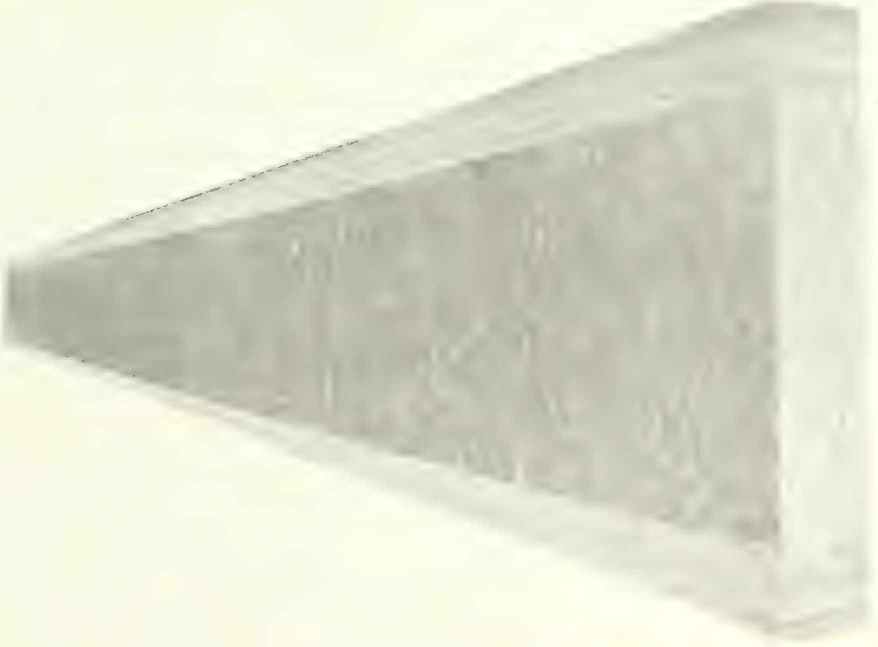

Figure 1.--COM-PLY joist used for framing floors of houses.

Potential manufacturers of COM-PLY floor joists, building code officials, and builders must be able to determine the strength, stiffness, durability, and dimensional stability of these joists in order to qualify them for safe, acceptable use in building homes. Suggested performance criteria for these properties in COM-PLY floor joists are presented in this report. With these standards, manufacturers can determine for themselves whether particular wood species and adhesives are satisfactory for joist production.

METHODS OF DEVELOPING PERFORMANCE STANDARDS

GENERAL

In recent years, code officials and the housing industry have advocated developing performance standards to replace traditional specification standards. A specification standard requires that components be spaced so many inches apart and be of a particular size and quality. A performance standard requires that components have sufficient strength, stiffness, durability, and other attributes to perform their intended functions. Specification standards tend to restrict development of new products, because only the materials and sizes specified can be used. Performance standards, on the other hand, allow for a wide range of materials and sizes as long as the product meets the levels of performance set forth by the standard.

In developing the Performance Standards for COM-PLY studs (Blomquist and others 1976), we collaborated with engineers of the Federal Housing Administration (FHA), U.S. Department of Housing and Urban Development (HUD). FHA engineers are increasingly concerned about the variation in strength of given building products used in housing. Because such products are often accepted on the basis of average strength values rather than the strength of the weakest element, the structures incorporating them may be unsafe. Thus, the FHA engineers wanted to use formulas that account for variation in the structural properties of building materials. The formulas we propose for COM-PLY floor joists use statistical methods to account for variation of strength and stiffness. The values obtained from these formulas can then be compared with pre-established minimum values for performance and the set of joists accepted or rejected for residential construction.

Tests indicate that strength and stiffness properties are normally distributed in populations of COM-PLY studs (Blomquist and others 1976). We can assume the same will be true of COM-PLY floor joists because the materials used will have the same range of properties. Using standard analytical statistics for a normal distribution (Dixon and Massey 1969), we can estimate how much the average strength of a sample of COM-PLY floor joists might vary from the average strength of the entire population from which the sample was drawn. We can also estimate how much the strength of the weakest or strongest floor joist will vary from the average, or what percentage of the entire population of floor joists we would expect to lie between specified upper or lower limits of strength. The variation from the average of any sample is measured by a statistic called the standard deviation and is designated by the letter S. Methods of calculating the standard deviation can be found in any standard statistics textbook.

The statistic t (Dixon and Massey 1969), along with the standard deviation S, provides a way of accurately predicting the range of population values. For a sample of N number of joists, the average test strength can be designated as $\bar{x}$. The average strength of the entire population could be higher or lower than the average found by testing a few joists. The lower limit of the average strength of the population can be estimated by the formula:

$$\bar{x} - \frac{t\,S}{\sqrt{N}}$$

The letter α indicates the level of significance used in selecting a value of t; in the performance standards to be presented, α has a value of 5 percent. In other words, the value of $\bar{x}$ will not be less than the calculated value unless a 1 in 20 sampling error has been made. The t distribution depends on the degrees of freedom (d.f.) of the sample. For the analyses in this report, d.f. = N - 1. Table 1 lists values of t for $\alpha = 0.05$ at degrees of freedom likely to be encountered in these performance standards.

Table 1.--Values of the statistic t at various degrees of freedom (d.f.) for $\alpha = 0.05$

d.f.	t	d.f.	t	d.f.	t	d.f.	t	d.f.	t
1	6.31	7	1.89	13	1.77	19	1.73	25	1.71
2	2.92	8	1.86	14	1.76	20	1.72	26	1.71
3	2.35	9	1.83	15	1.75	21	1.72	30	1.70
4	2.13	10	1.81	16	1.75	22	1.72	40	1.68
5	2.01	11	1.80	17	1.74	23	1.71	60	1.67
6	1.94	12	1.78	18	1.73	24	1.71	120	1.66

An example will illustrate how to select a value of $t_{0.05}$. Assume 20 floor joists were tested. Then N = 20 and there are N - 1 or 19 degrees of freedom. From table 1 the value of $t_{0.05}$ for d.f. = 19 is 1.73.

Another example will illustrate the calculation of the lower limit of the population average. Assume 20 floor joists were tested and found to have an average ultimate or failure strength, $\bar{x}$, of 196.9 pounds per linear foot of bending load with a standard deviation S of 30.8 pounds. The value of $t_{0.05}$ for d.f. = 19 is 1.73. Substituting the values of $\bar{x}$, t, S, and N in the formula for estimating average strengths of the population, one obtains

$$196.9 - \frac{(1.73 \times 30.8)}{\sqrt{20}} = 196.9 - 11.9 = 185.0$$

or 185.0 pounds per linear foot. In other words, after testing 20 COM-PLY joists we would be 95 percent confident that the true averages of joist strength are not less than 185 pounds per linear foot. Thus, our best estimates of the average population strength to use for design is 185 pounds per linear foot of bending load.

For a normal distribution of strength properties, 95 percent of the population is likely to be stronger than $\bar{x} - t_{0.05}S$. This is usually referred to as the 5 percent lower exlusion limit.

The various adjustments of the average test values of the sample can be combined into one expression as follows:

$$\bar{x} - \frac{t_{0.05}S}{\sqrt{N}} - t_{0.05}S$$

The first term of this expression is the average value of some attribute of the test sample, the second term corrects the average sample value to estimate the lower or safe limit of the population average for that attribute, and the third term estimates the 5 percent lower exclusion limit.

The expression is further modified when used for strength computations, as follows:

$$\left[\bar{x} - \frac{t_{0.05}S}{\sqrt{N}} - t_{0.05}S\right] \frac{F_r}{F_s F_t}$$

where F_r, F_s, and F_t are adjustment factors for load sharing, safety, and duration of load. The value of the total expression is called the minimum adjusted load.

Floor joists are commonly used in conjunction with several joists in a given floor. When three or more floor joists make up a frame, the load-carrying capacity of an individual joist is in effect increased 15 percent through the benefits of load sharing with adjacent members (NFPA 1977). The term F_r accounts for load sharing and is used to modify the general expression whenever bending strengths are being evaluated. For this application, the value of F_r is 1.15.

Without the safety factor F_s, some of the weaker joists might fail when the design load is applied or an accidental overload occurs. A value of 1.5 for the safety factor was selected for these standards. This factor means that 95 percent of the pieces would withstand a 50 percent overload before any failures occur. This figure is a conservative estimate because other parts of the structure such as floor sheathing contribute strength and stiffness that is generally not accounted for by the simplified design methods used.

The factor for duration of load, term F_t, is used to account for the difference between the period the test load was applied and the period the service load, such as live load, is expected to be applied. In general, wood products can sustain heavier breaking loads for short periods (1 second or 1 minute) than for long periods (several months or years). Laboratory tests to evaluate mechanical strength properties of wood are made in a relatively short time (usually 5 to 20 minutes), whereas service loads may continue for the life of the structure. Therefore, laboratory test values for strength usually are too high and must be adjusted downward to represent conditions under service load. To determine the value of F_t, the factor for duration of the test load is divided by the factor for duration of the service load (Hunt and others 1973; ASTM 1975a). For example, if the average test period is 15 minutes (factor for duration of load, 1.57) and the service load is a normal load (factor for duration of load, 1.0), then the value of F_t is 1.57/1.0 or 1.57.

Values of bending deflection are usually based on average values rather than on minimum values as for strength. The greatest average deflection would be of the most concern to a designer. The greatest average deflection of a population can be estimated from test data by the following expression:

$$\bar{d} + \frac{t_{0.05}S}{\sqrt{N}}$$

In this expression, $\bar{d}$ is the average deflection in a test sample of N number of specimens. The other terms have been previously defined. A plus sign rather than a minus sign is used in the expression because the greatest average population value for deflection is to be estimated, not the least.

An example will illustrate how to use the expression. Population deflections can be estimated as follows for a sample of 20 test floor joists with an average test bending deflection, $\bar{d}$, of 0.321 inch and a standard deviation of 0.049 inch under a bending load of 50 pounds per square foot of floor area:

$$\bar{d} + \frac{t_{0.05}S}{\sqrt{N}} = 0.321 + \frac{1.73\ (0.049)}{\sqrt{20}} = 0.340 \text{ inch}$$

Thus, there is one chance in 20 that the average deflection of the population would exceed 0.340 inch. This amount is called the adjusted deflection.

In general, the method proposed here for evaluating strength and stiffness is to test a sample of COM-PLY floor joists for these properties according to definite procedures and then adjust the values to account for variation in the entire population and other factors, as outlined above. The population of floor joists can then be accepted or rejected for home building according to whether the adjusted values equal or exceed the performance standards previously judged acceptable by building code, FHA, and other officials, as discussed in the following sections.

Performance standards are not given here for end bearing of joists or for joists supported by nails or joist hangers. Floor joist designs are seldom controlled by the method of support. However, if a manufacturer uses particleboard having a density of less than 35 pounds per cubic foot, or an internal bond of less than 85 pounds per square inch, or a board that exhibits splitting when nailed, it may be necessary for the manufacturer to conduct performance tests on strengths of various methods of support to show the joist can support adequate loads for housing.

The Wood Products Research Unit of the Southeastern Forest Experiment Station in Athens, Georgia, is studying the strength and rigidity of COM-PLY joists in end bearing for joints made with nails or joist hangers. A suggested performance standard for COM-PLY joists in these applications will be included in the results of a forthcoming study.

STRUCTURAL STRENGTH AND STIFFNESS

Floor joists are selected primarily to meet strength and stiffness requirements. Strength requirements depend upon the loads to be carried. Stiffness requirements place an arbitrary control on deflection under load. Stiffness is also important in limiting vibrations from moving loads--often a cause of annoyance to the occupants. Whittemore and others (1948) have shown that the largest load imposed on floor joists in a residence is not caused by furniture but by a crowd of people. Such loads average 40 pounds per square foot of floor area and may occur in any room at any time. These findings have been used in evolving the combination of strength and stiffness criteria for a floor design.

The structural design criteria for COM-PLY floor joists are similar to those recommended by the National Forest Products Association and the Western Wood Products Association and currently accepted by the U.S. Department of Housing and Urban Development: (1) For all rooms except sleeping areas and floored attics, the design criteria for deflection are based on a live load of 40 pounds per square foot of floor area and the adjusted deflection can be no greater than the span in inches divided by 360. For strength, the adjusted load can be no less than a live load of 40 pounds plus a dead load of 10 pounds per square foot of floor area. (2) For sleeping areas and floored attics, the design criteria for deflection are based on a live load of 30 pounds per square foot of floor area and the adjusted deflection can be no more than the span in inches divided by 360. For strength, the adjusted load can be no less than a live load of 30 pounds plus a dead load of 10 pounds per square foot of floor area. For both criteria, the design and test span of the floor joists is the clear distance between joist supports.

The test method to be described involves two concentrated bending loads acting at the quarter points of the test span rather than a uniformly distributed bending load. The quarter-point method is simpler to set up in most laboratories with universal testing machines. A beam bent with quarter-point loads will deflect more at midspan than a beam bent with the same amount of uniformly distributed load. Since two concentrated bending loads are used in this performance standard, the increased deflection must be accounted for. The formula used to find the midspan or maximum deflection (d_1) for a simple beam loaded with quarter-point loading is:

$$d_1 = \frac{49.5 \ PL^3}{EI}$$

where P = the quarter-point load in pounds, L = the test span in feet, E = the modulus of elasticity in pounds per square inch, and I = the moment of inertia of the cross section in inches to the fourth power.

The formula used to find the midpoint or maximum deflection (d_2) for a simple beam with a uniformly distributed load is:

$$d_2 = \frac{22.5 \ wL^4}{EI}$$

where w = load in pounds per foot of length.

The ratio of increased deflection of two concentrated loads to a uniformly distributed load is:

$$\frac{d_1}{d_2} = \frac{49.5 \ PL^3}{22.5 \ wL^4}$$

When applied loads are equal for the two types of beam loading, then 2 P = wL. Substituting the value of 2 P for wL, the ratio becomes:

$$\frac{d_1}{d_2} = \frac{49.5 \ PL^3}{45.0 \ PL^3}$$

Therefore, $d_1 = 1.1 \ d_2$ or the midspan deflection under concentrated quarter-point loads is 1.1 times as much as the midspan deflection of the same amount of uniformly distributed load.

The adjusted maximum deflection of a set of floor joists under a uniformly distributed design load is equal to the test span in inches divided by 360. For example, if the test span is 11.5 feet or 138 inches, then the maximum allowable deflection under a uniformly distributed design load would be 138/360 or 0.38 inch. However, if the quarter-point load method was used, the adjusted maximum allowable deflection would be 1.1 times 0.38 inch or 0.42 inch.

DURABILITY

Like solid wood joists, COM-PLY joists should be durable enough to withstand exterior weathering on the job site and the moisture and temperature changes that occur after the joists are installed. Since the COM-PLY joist is a glued wood product, the durability of the resin bonds used to make the particleboard core and the adhesive bonds used in laminating the veneers to the core are of major interest.

To set a level of performance, we decided how much outdoor weathering would be sufficient to test the durability of the COM-PLY joist. In arriving at a test for durability, we collaborated with scientists and engineers from the National Particleboard Association, the Forest Products Laboratory, and HUD. The following points were considered in devising the test:

(1) Duff (1978) has shown that the changes in moisture content of solid wood joists over damp crawl spaces would not be as great as changes occurring in joists exposed to exterior weathering. The durability of COM-PLY joists would be affected less by moisture changes after installation in a house than by those changes that could occur on the job site.

(2) The most severe weathering to which a builder might subject a COM-PLY joist would be 1 year of unprotected, direct exposure of the floor system on the job site. Such exposure should not cause significant loss in strength or stiffness. Although 1 year of outdoor weathering would constitute a logical durability test of COM-PLY joists, tests of this duration are impractical. Building officials and manufacturers would prefer a durability test that requires a much shorter time, such as 1 or 2 weeks.

(3) At present, there is no known accelerated laboratory test that would be equivalent to 1 or 2 years of exterior exposure of COM-PLY joists. However, one test method, the ASTM D 1037-72a accelerated aging test (ASTM 1975b), has demonstrated good correlation with several years of outdoor weathering of particleboard products (Hann and others 1962). This testing procedure involves wetting and drying at high temperatures and has proven satisfactory for determining the long-term durability of exterior particleboard products.

A modification of the ASTM D 1037-72a test (ASTM 1975b) was therefore selected as an interim method of testing the durability of COM-PLY joists. The freezing cycle was omitted since freezing has far less effect on durability than does wetting and drying at high temperatures. Collaborators decided that, after exposure to the modified aging test, COM-PLY joists should retain at least 50 percent of their original strength and that deflection should not increase more than 100 percent.

The Wood Products Research Unit at Athens, Georgia, is subjecting COM-PLY joists to long-term outdoor exposure. These tests may not only show that the acceptable levels of durability can be raised but also provide guidance in developing a more realistic laboratory test. If so, this standard will be changed.

DIMENSIONAL STABILITY

All wood products tend to undergo dimensional changes and warpage when their moisture content changes. Thus, during weathering, COM-PLY joists can change in size (thickness, width, or length), the amount of change depending on their dimensional stability. Warpage of a joist is any variation from a true plane surface. For COM-PLY joists the most critical types of warpage are crook, bow, and twist as defined by lumber-grading rules. Too much warpage or change in size could make the joists unsuitable for home building.

To formulate a method for evaluating dimensional stability and warpage, we collaborated with the same advisers who helped develop the test for durability. The following points were considered in devising the test:

(1) The most severe swelling and warping results from soaking dry joists in water until each joist is saturated. Heebink and Hefty (1969) have demonstrated that the greatest increase in thickness of particleboard without wax occurs during the first 24-hour cycle of water soaking. On the basis of this study and recommendations by the National Particleboard Association, we decided to precondition the COM-PLY joists to a moisture content of 10 ± 2 percent, soak them for 24 hours, and then measure their warpage and size change.

(2) The percentage of increase in thickness, width, and length after soaking in water should not be greater than corresponding changes for solid wood joists. This limit is essential for width and length because substantial changes in these dimensions could result in an uneven floor. Swelling in thickness is less critical because such swelling occurs in the floor cavity between joists and probably would not affect appearance of the floor. Similarly, warpage of COM-PLY joists should not exceed what has been found acceptable for sawn lumber joists.

The acceptable limits of dimensional change and warpage after soaking, as determined by tests on sawn lumber joists, are listed in the performance standard for dimensional stability elsewhere in this report. Preliminary studies by Duff show that critical changes such as warpage and swelling across the width are much less for COM-PLY joists than for sawn lumber joists.

PERFORMANCE STANDARDS FOR COM-PLY JOISTS

GENERAL

When a sample of COM-PLY floor joists meets the performance standards presented here, then floor joists manufactured to essentially the same specifications are acceptable for use in single- and multi-family dwellings. Such floor joists will be acceptable to any building code agency that has adopted these performance standards as a method of code approval. Performance evaluation for strength, stiffness, durability and dimensional stability shall be made for joists of each cross sectional size marketed unless the approving building code agency chooses not to require a specific size of joist to be evaluated or elects to waive a specific portion of the standard. The sample tested must be randomly selected from COM-PLY floor joists representative of those proposed for commercial use.

The initial sample submitted to a testing laboratory must contain 10 specimens. If this sample meets all the performance levels required, then the design is considered acceptable. If the results of any test are slightly below the level required, then 10 additional specimens may be tested and the results averaged with those of the previous test to raise the results to an acceptable level. There is seldom any advantage to testing more than 30 floor joists for a given property.

Evaluating the performance of COM-PLY floor joists with these standards requires that a numerically expressed value or standard level of strength and stiffness be established for acceptance. A laboratory test for strength and another for stiffness are then performed on the samples. For either test, the numerical test value is adjusted to account for variation in the population of floor joists as well as factors of safety, duration of load, and load sharing as they apply. This adjusted value is then compared with the standard level for that property, and the joists are accepted only if the adjusted strength value equals or exceeds the standard level and the adjusted deflection is equal to or less than the standard level.

When possible, the manufacturer should provide the testing laboratory with the following information on the COM-PLY floor joist submitted:

- Thickness of veneers
- Species or combinations of species used for veneer
- Quality of veneer
- Type and spread rate of laminating adhesive
- Geometry of wood particles in the particleboard
- Percentage and type of particleboard binder

- Percentage and type of particleboard wax
- Internal bond of particleboard
- Density of particleboard
- Thickness swelling of particleboard
- Linear expansion of particleboard
- Modulus of elasticity of particleboard
- Modulus of rupture of particleboard
- Trademark identifying specifications to which COM-PLY floor joists were made

Properties of the particleboard core such as internal bond, density, thickness swelling, linear expansion, MOE, and MOR should be determined by the standard methods set forth in ASTM D 1037-72a (ASTM 1975b).

All specimens must be tested at a moisture content of 10 ± 2 percent. This moisture content can be attained by conditioning joists to constant weight under controlled temperature and relative humidity: for example, $80^\circ \pm 6^\circ$ F ($27^\circ \pm 3^\circ$ C) and a relative humidity of 65 ± 1 percent, or an equivalent combination.

After completing the tests, the laboratory should report the following information to the manufacturer:

- Number of specimens tested in each evaluation
- Test values for individual specimens
- Average test values
- Standard deviation of test values
- Computation of adjusted values for the population of joists
- Explanatory notes on any unusual modes of failures

STRUCTURAL STRENGTH AND STIFFNESS

Standard Level

A COM-PLY floor joist to be used in all rooms except sleeping areas and floored attics must safely withstand a transverse bending load equivalent to 50 pounds per square foot (psf) of uniformly distributed floor load (40 psf of live load plus 10 psf of dead load). This requirement is the standard level for strength. Furthermore, a COM-PLY floor joist used the same way cannot deflect more than 1.1 times the clear span in inches divided by 360 when two concentrated loads are placed at quarter points. This limit is the standard level for stiffness. The quarter-point loads are equivalent to 40 psf of uniform floor load on the test span. The standard levels for strength and stiffness of COM-PLY floor joists to be used for sleeping areas and attic floors are the same except that the amount of the two concentrated loads placed at quarter points is reduced by 10 psf of uniform floor load.

Laboratory Test

The bending load can be applied with a universal testing machine, hydraulic cylinders, or any equivalent device. Because most laboratories use the universal testing machine, the loading method most appropriate for such a machine will be described. With this method, two concentrated bending loads are applied to the specimen (fig. 2). For a given loading, this method will induce the same maximum bending moment in the specimen as a uniformly distributed bending load. However, the maximum bending moment is continuous between the concentrated loads, whereas it occurs only at midspan with uniformly distributed loads. With either loading method, the load per linear foot is computed by dividing the total downward load by the length of the test span.

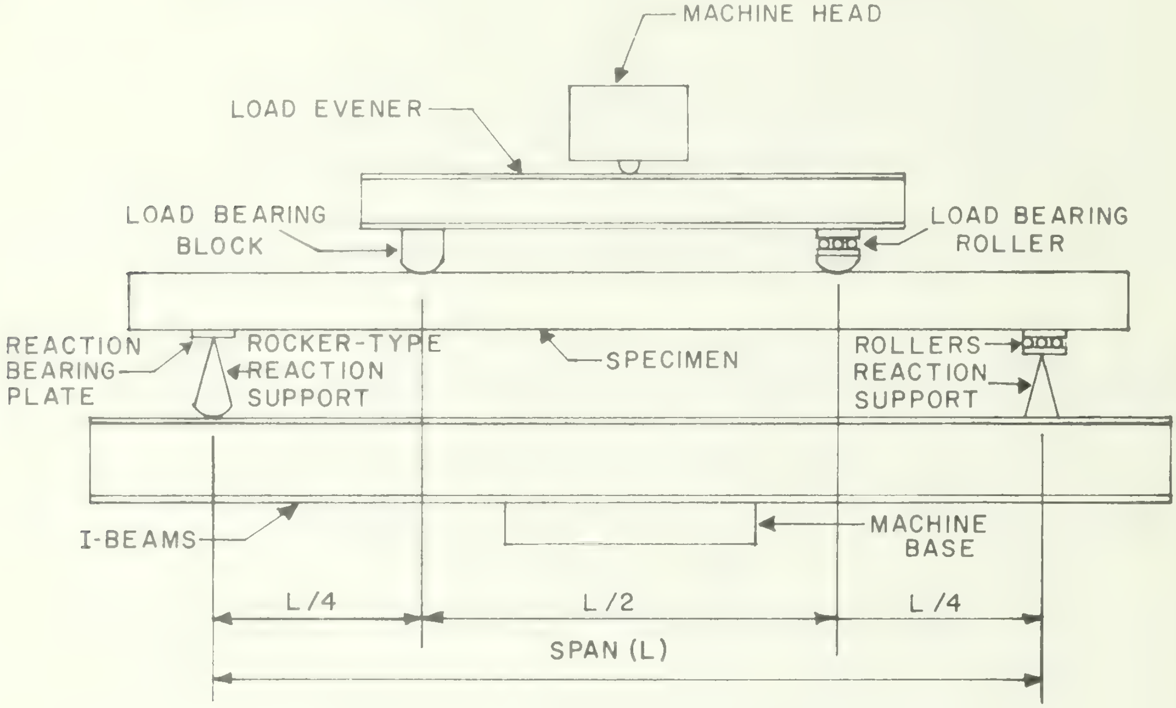

Figure 2.--Loading method for bending test.

The COM-PLY test specimen rests on metal bearing plates to prevent damage at the point of contact between it and the reaction supports. The bearing plates rest on rollers and a fixed knife-edge reaction support or on a rocker-type knife-edge reaction support so that shortening and rotation of the specimen at the supports as a result of deflection will be unrestricted (ASTM 1975c).

Lateral support must be provided at points about halfway between the reaction support and the load point. Additional lateral supports may be used as required to prevent lateral buckling. Each lateral support must restrict lateral buckling and allow vertical movement without frictional restraint.

The load is applied to the specimen at quarter points through bearing blocks across the full specimen width. The loading surface of the blocks has a radius of curvature equal to two to four times the specimen depth for a chord length at least equal to the depth of the specimen. Metal bearing plates and rollers are used in conjunction with one load-bearing block to permit specimen deflection without restraint. All bearing plates, blocks, and rollers extend across the entire width of the specimen and are provided with rotatable bearings or shims to ensure full contact between the specimen and both loading blocks.

The midspan deflection of the test specimen during loading is measured with a dial indicator that reads to the nearest 0.001 inch. The dial indicator is mounted on a frame or yoke supported on pins through the specimen at the neutral axis and directly over the specimen supports (fig. 3). This arrangement prevents the deflection readings from being affected by any settling of the supports.

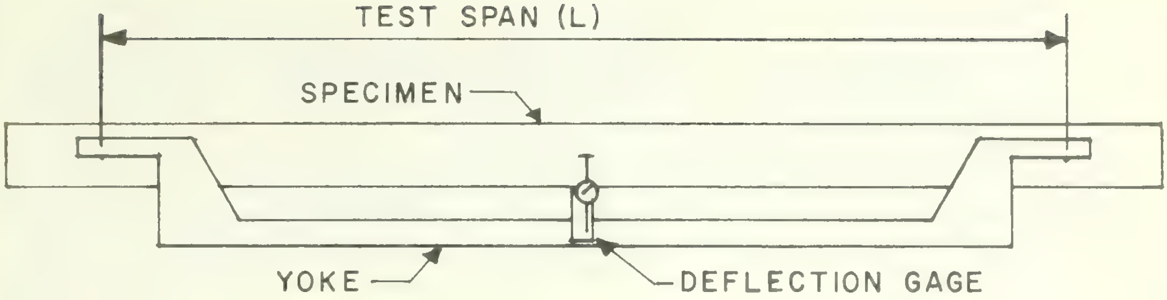

Figure 3.--Dial gage mounted on a frame with supports at ends of the specimen.

The first step of the test procedure is to place the specimen on the bearing supports. Then place the gage frame and dial gage on the support pins at the ends of the specimen. Set the gage reading at zero and apply a continuously increasing bending load at a constant rate of load (pounds per minute) or head speed (inches per minute) until the specimen fails. Ultimate load or failure is reached when deformation occurs at an increasing rate per unit of time with no increase in load or when the test specimen collapses. Select a rate of load or head speed that will result in failure in about 10 minutes--in not less than 6 nor more than 20 minutes. During loading to failure, read the dial gage and record the amount of deflection at sufficient intervals to obtain data for plotting a load-deformation curve. Load intervals of 100 pounds are typical. Just prior to failure, remove the support yoke to protect the gage from an instantaneous impact. For each specimen, record ultimate load and the mode and location of failure. In the test report, also record a complete description of the specimen, its moisture content, the average deflection a uniformly distributed floor load of 50 psf would impose upon it, the testing apparatus, and the method of loading.

Determining Acceptability

Proposed COM-PLY joists will be qualified for strength and stiffness performance on the basis of tests that assume a 16-inch joist spacing, a total design load of 50 psf, and the maximum clear span specified by the manufacturer. The results may be extended to other spacings, loadings, or spans by using standard formulas found in structural engineering texts or handbooks and by following established engineering theory for making such modifications. For strength modifications, the average safe resisting moment from the test is easily computed and used to determine other combinations of spacings, loadings, and spans. For stiffness modifications, the effective average stiffness factor, EI, from the test is easily computed and used to determine other combinations of spacings, loadings, and spans.

The average values for strength and stiffness for a test sample of floor joists must be adjusted to determine the actual or design load such floor joists can be expected to carry safely. These adjusted values must then be compared with the performance standard. For strength, the adjusted value is computed by the following formula:

$$W = \left[\bar{w} - \frac{t_{0.05}S}{\sqrt{N}} - t_{0.05}S \right] \frac{F_r}{F_s \; F_t}$$

where:

W = adjusted value for load in pounds per linear foot of floor joist

$\bar{w}$ = average ultimate test load in pounds per linear foot of floor joist

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of ultimate test loads in pounds per linear foot of floor joist

N = number of test specimens

F_r = allowable increase for load sharing among adjacent floor joists in typical floor framing; use 1.15. When a COM-PLY joist is used for a single-member beam application without load sharing, the value of F_r is 1.0.

F_s = safety factor; use 1.5

F_t = adjustment for the ratio of the duration of the test load to the duration of the service load. In this case, the service load is assumed to be a normal load, and the factor for the duration of this load is 1.0. If the test load is applied over an average period of 15 minutes, the factor for the duration of this load is 1.57. In this example, the test load is applied faster than the service load, so the adjustment factor is 1.57/1.0 or 1.57 (Hunt and others 1973; ASTM 1975a).

For stiffness, the adjusted value is computed by the following formula:

$$D = \bar{d} + \frac{t_{0.05}S}{\sqrt{N}}$$

where:

D = adjusted value for midspan deflection in inches

$\bar{d}$ = the average midspan deflection of N test joists when the applied load is 53.33 pounds per linear foot

$t_{0.05}$ = statistical t at 0.05 confidence level for N - 1 degrees of freedom

S = standard deviation of midspan deflections

N = number of specimens

The stiffness of the joist design is acceptable if the value for D is 0.00306L where L is the test span in inches.

DURABILITY

Standard Level

The standard for durability requires that a group of control specimens be tested for structural strength and stiffness as required in the performance standard. A second group of specimens is then exposed to accelerated aging and tested for strength and stiffness. All specimens should be 8 feet long and should be tested over a 90-inch span.

The adjusted value for bending strength after accelerated aging must be at least 50 percent of the adjusted value for unexposed joists. The adjusted value for deflection after accelerated aging must not be more than 100 percent greater than the adjusted value for deflection of unexposed joists.

Laboratory Test

The second group of specimens is subjected to six cycles of accelerated aging, each cycle consisting of five exposures at varying temperatures and moisture contents. The five exposures that make up an accelerated aging cycle are as follows:

(1) Immerse all specimens for 1 hour in a tank filled with tapwater maintained at 120° ± 3° F (49° ± 2° C). The immersion tank (fig. 4) should be essentially free from corrosion. Separate the specimens so that all surfaces are in contact with the water.

(2) Place the specimens in a closed vessel and spray them for 3 hours with steam at atmospheric pressure. Maintain the temperature inside the vessel at 200° ± 5° F (93° ± 3° C).

(3) Place the specimens in a dry kiln or drying oven and circulate air around the specimens at the rate of 100 to 300 feet per minute for 3 hours (fig. 5). The circulated air must be heated to 210° ± 3° F (99° ± 2° C) with a relative humidity of 40 ± 5 percent. Space the specimens at least 3/4 inch apart so that all surfaces are exposed.

(4) Repeat exposure 2.

(5) Repeat exposure 3, but maintain it for 18 instead of 3 hours.

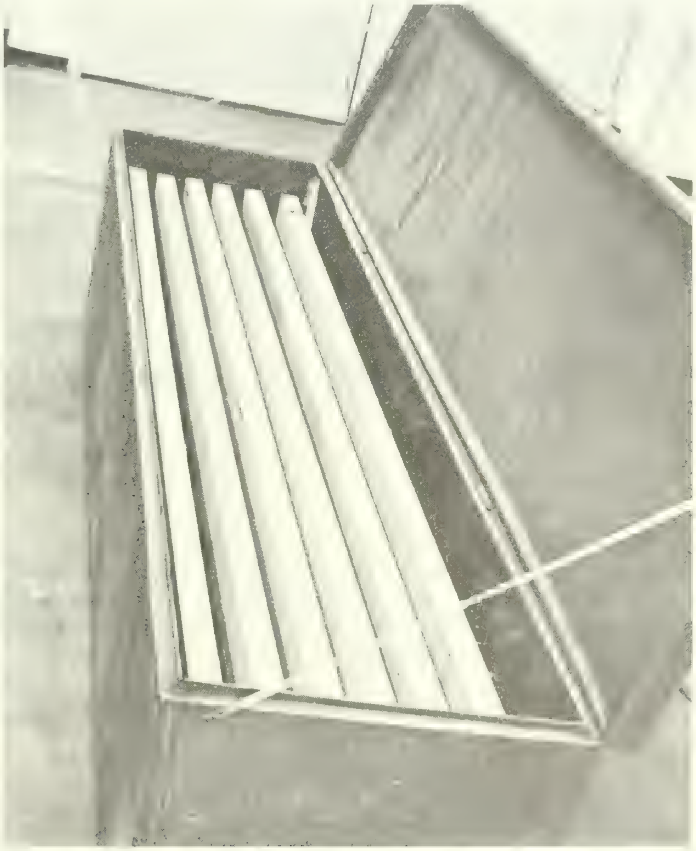

Figure 4.--Tank used at the Forestry Sciences Laboratory for water soaking and steaming specimens.

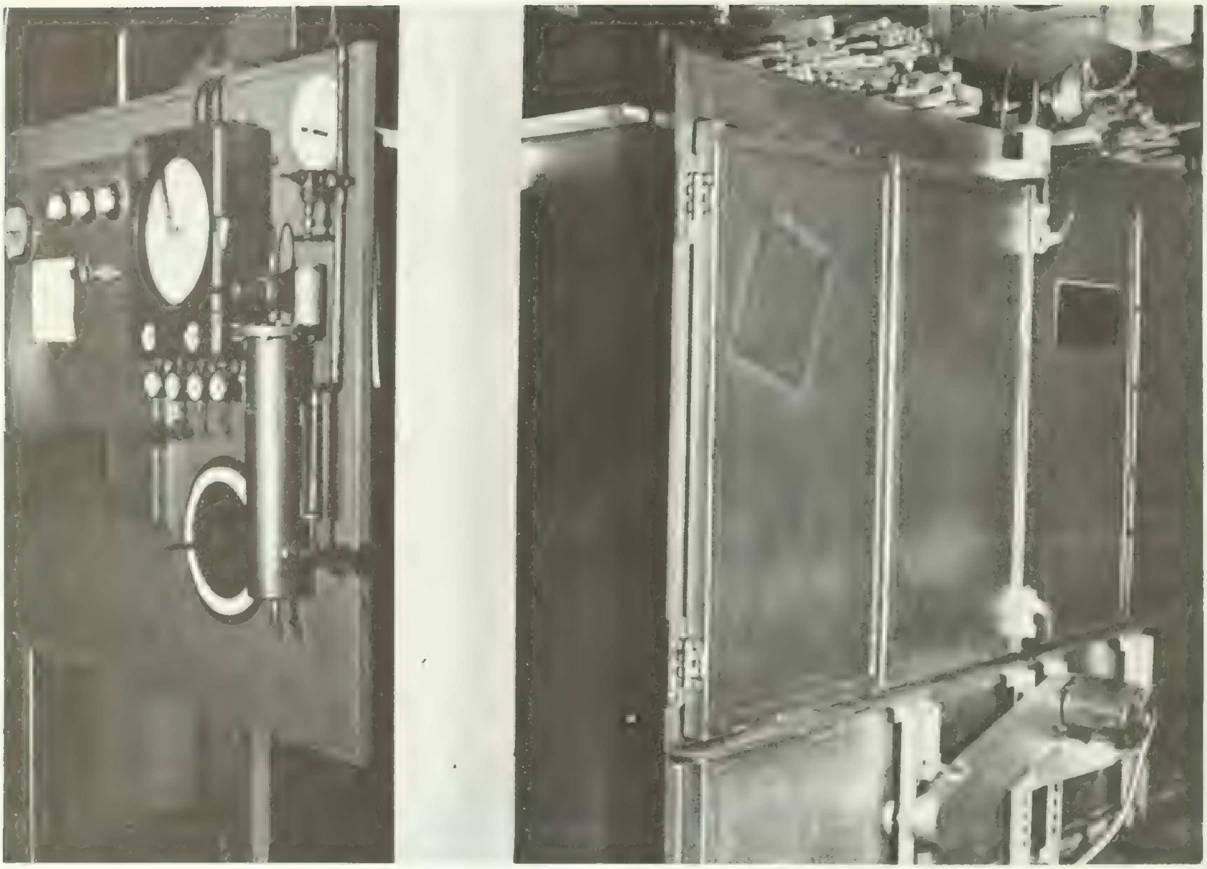

Figure 5.--Dry kiln used at the Forestry Sciences Laboratory for drying specimens.

Inspect the specimens after each cycle of five exposures for any visible sign of delamination or other disintegration and describe such signs in the test report.

After completing six cycles of accelerated aging, bring the specimens to a moisture content of 10 ± 2 percent by conditioning them to constant weight under controlled temperature and relative humidity. Then test the specimens for structural strength and stiffness. The rates of load or head speed during loading may have to be decreased so that ultimate loads occur in not less than 6 nor more than 20 minutes.

Determining Acceptability

The test values for strength and stiffness must be adjusted by the same formula used in the previous test. The adjusted value for strength after cyclic exposure cannot be less than 50 percent of the adjusted value of the control group. The adjusted value for deflection after exposure cannot be more than 100 percent greater than the adjusted value of the controls.

DIMENSIONAL STABILITY

Standard Level

The standard levels for dimensional stability require that, after water soaking, average dimensional increases of all COM-PLY specimens not exceed 8.0 percent for width and thickness and 0.1 percent for length and that the average warpage not exceed that described as "Light" in lumber grading rules for the length and width nearest that of the specimen size.

Laboratory Test

Bring each specimen to a moisture content of 10 ± 2 percent by conditioning it to a constant weight under controlled temperature and relative humidity. Then, at quarter and midpoints along the length of each specimen, measure its width and thickness at the center of each face to the nearest 0.001 inch. Mark the points of measurement on the specimens. Then place each specimen in a metal frame so that one end rests against a fixed stop and the other end rests against the stem of a dial gage incremented to 0.001 inch (fig. 6). A calibrated rod measured to the nearest 0.1 inch may be used to determine the distance between the fixed stop and the gage stem when the dial gage reads zero. Record the length of each specimen for later comparison after water soaking. Finally, measure the amount of warpage in all specimens according to the methods found in the lumber grading rules.

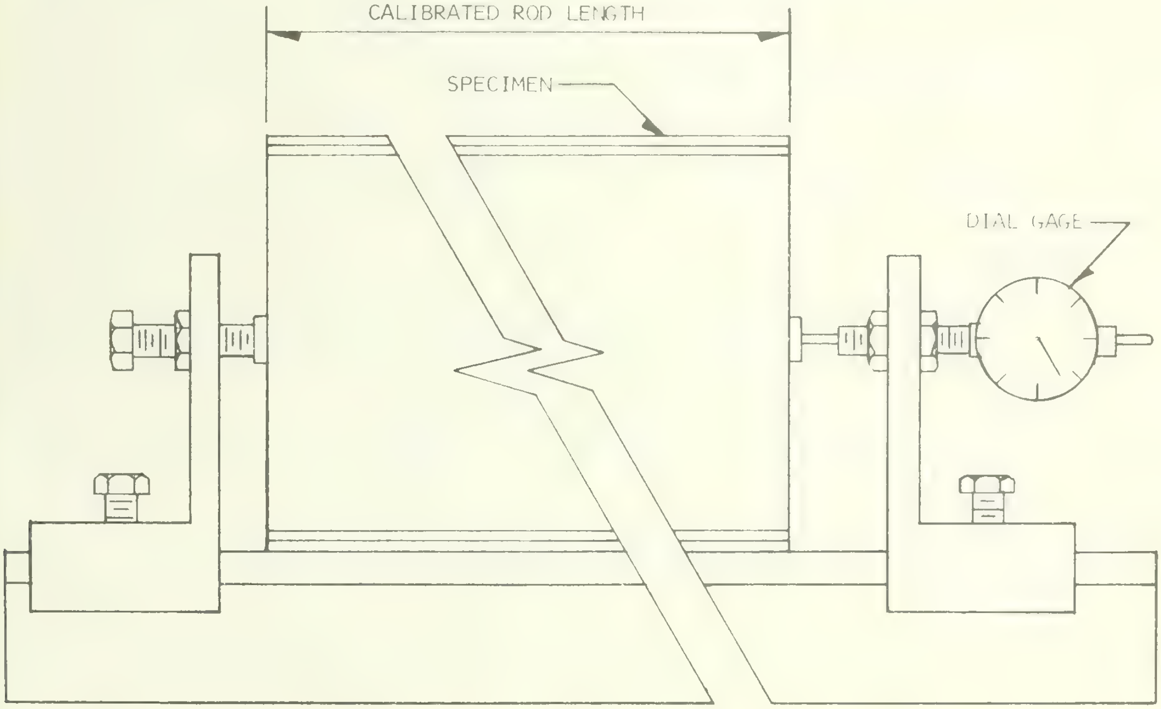

Figure 6.--Apparatus for measuring length of joists before and after soaking.

After all specimens have been measured, immerse them in water at 68° ± 6° F (20° ± 3° C) for 24 hours. Separate the specimens with spacer blocks so that all surfaces are in contact with the water. After the soaking period, remeasure all specimens at the same locations to obtain relative increases in width, thickness, and length. Then measure the amount of warpage in each specimen.

Determining Acceptability

Compute the average percentage of increase in width, thickness, and length for the test specimens after water soaking, as well as the average warpage in bow, twist, and crook. These averages shall not exceed the standard levels for dimensional stability and warpage of the joists.

DISCUSSION

These standards should prove useful to potential manufacturers of COM-PLY joists. After selecting the thickness and number of veneers, species of wood, laminating adhesive, and particleboard resin binder that appear economically feasible to use, the manufacturer can determine from these standards whether the proposed design is acceptable for house construction.

Although these standards were developed for COM-PLY joists in floor framing, they could also be used to evaluate the performance of other floor joists made from wood composites. For example, with these standards, floor joists made entirely of particleboard, wood veneer laminates, or hardboard could be evaluated for acceptability in home building.

Further research on evaluating the durability of COM-PLY joists is needed so that a laboratory test well correlated with outdoor weathering can be developed.

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This report presents standards for evaluating the strength, stiffness, durability, and dimensional stability of COM-PLY floor joists. The standards set levels of acceptable performance for joists used in residential construction. Test methods for evaluating performance are described in detail. Manufacturers can use these standards to determine whether COM-PLY floor joists they produce are adequate for use in building homes. Building code officials can use these standards for accepting or rejecting COM-PLY floor joists for use within the code jurisdiction.

KEYWORDS: Floor joist performance, floor joist strength, floor joist stiffness, floor performance, floor framing.

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THEORY FOR NEW DIRECTIONS IN FOREST MANAGEMENT

by

Stephen G. Boyce

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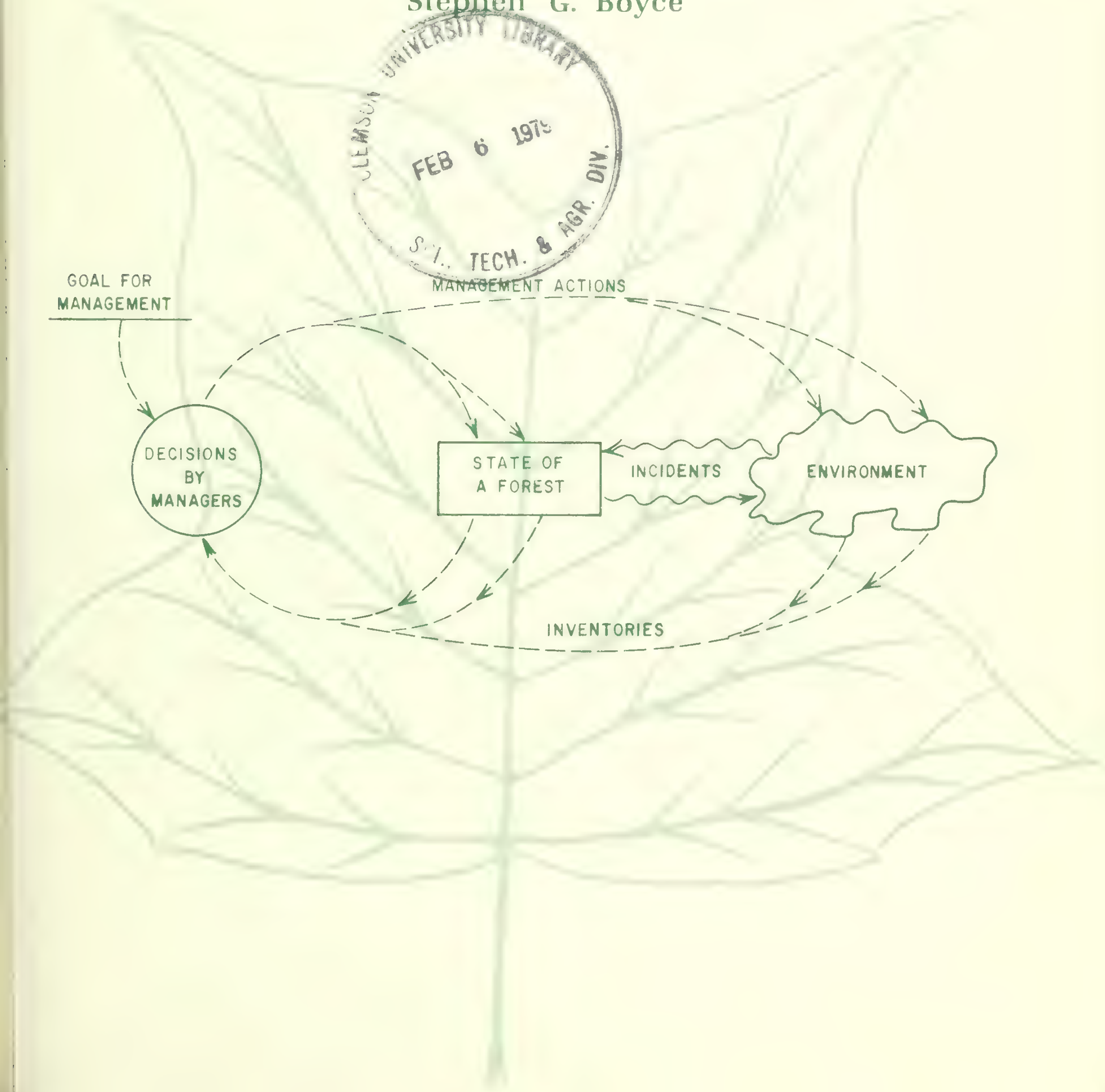

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THEORY FOR NEW DIRECTIONS IN FOREST MANAGEMENT

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Abstract. — The natural, unmanaged forest is an aimless system. There are no natural goals for the community. With time and natural mortality, the physical and chemical makeup of the forest changes from one irreversible state to another. Described here is the logic for four bionomic theories which underlie new directions of forest management designed to harmonize actions to obtain multiple forest benefits. These theories provide the bases for management to direct the self-organizing biological systems to produce a desirable combination of benefits.

KEYWORDS: Bionomic theories, multiple benefits, management, logic, constraint quanta (CQ).

The new direction for forestry is to systematically provide multiple benefits, rather than a single benefit such as fuelwood, timber, water, or game. Change to the new direction has been underway for more than 20 years. But, worldwide, relatively few forests are systematically managed for multiple benefits. In his keynote address to the Seventh World Forestry Congress, Steenberg (1972) noted: "Whatever the total complex of reasons for the present situation, the important thing is to grasp the true significance of this historic opportunity for forestry: the current resonance between the ideals of the small enlightened group of renewable-resources managers and society at large."

The new direction requires harmonized actions for the joint production of many tangible and nontangible benefits. One benefit, often overlooked, is to provide for the livelihood of many of the world's wild plants and animals. These plants and animals are reservoirs of germ plasm that can provide us with new kinds of domestic animals and plants, medicinal compounds, and organic chemicals. For the immediate future, it is necessary to provide fuelwood, timber, water, game, and recreational opportunities. In addition, it is important that management provide for the continued natural evolution and natural extinction of endemic species for the distant future. The four bionomic theories described here can be used to bring about these new directions in the management of forests.

THE THEORIES AND THE PRACTICE

The theories are restated from Boyce (1977).

1. Each living organism and its environment form an individualistic system with the goal of survival and the dynamics of systems with negative feedback loops.

2. The mortality of infinite numbers of individualistic systems organizes survivors into communities without goals and with the dynamics of systems without feedback loops.

3. The flows of energy, nutrients, carbon dioxide, water, and organic materials are unidirectional and have the dynamics of systems without goals and without feedback loops.

4. The kinds and proportions of various states of organization determine the kinds and proportions of multiple benefits available from a forest.

The first theory describes the organism and its environment as inseparable parts of an individualistic system. This system is viewed as the basic unit of communities. The organization of forest communities is then explained in the second theory by the behavior, especially mortality, of the individualistic systems. (Behavior of individualistic systems is determined by the mechanisms of control and communication.) The unidirectional flow of energy and materials is explained by the third theory. The fourth theory relates the states of forest organization to the livelihood of endemic organisms, natural evolution and natural extinction of organisms, and the availability of human benefits.

The practical use of the theories is to design management schemes that will direct self-organizing, individualistic systems to bring about desired states of forest organization. From the theories and direct observations, dynamic changes in forests, such as mortality, are irreversible. The flows of energy and matter through the land are delayed and used by organisms to build and maintain functional and structural order, but this order is physically and chemically unstable. The continued maintenance of order is dependent on mortality, which increases the dissipation of energy and materials. This dissipation creates nonequilibrium conditions that sequentially and continually shift the proportion of old-growth stands and similar elements of forest organization from one irreversible state to another.

These self-organizing mechanisms and natural nonequilibrium conditions can be directed by regulating the rates of timber harvest and the size of openings formed by harvesting. These actions produce planned mortality rates, which result in the maintenance of a desired order in the distribution of habitats. Directed mortality is the primary method to bring about habitats for desired game animals, to increase streamflow, to produce fuelwood and timber, and to change the esthetic appearance of forests. Thinnings, changes in the composition of species, and the formation of wildlife openings all require changes in the natural rate of mortality. Thus, mortality is used to systematically and harmoniously provide multiple benefits.

For example, if one knows the proportional distribution of stand condition classes such as seedlings, saplings, poles, mature timber, and old-growth stands and the area of each stand, then the opportunity for the livelihood of specific plants and animals can be assessed. And, if all possible combinations are available, then from the bionomic theories, a livelihood should be available for each endemic organism.

For illustration, consider the habitat characteristics for the flicker woodpecker. In the deciduous forests of Eastern North America, this bird feeds mostly on the surface—on lawns, pastures, and in recently harvested forest openings that are larger than 0.2 ha. Nesting and resting are typically in margins of forests that contain large dead trees and branches (Scott and others 1977). These characteristics can be expressed by three diagrams (figs. 1, 2, 3). Feeding

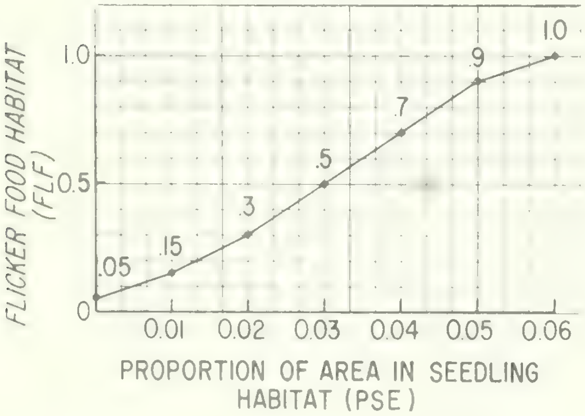

Figure 1.—Flicker food habitat index versus the proportion of area in seedling habitat.

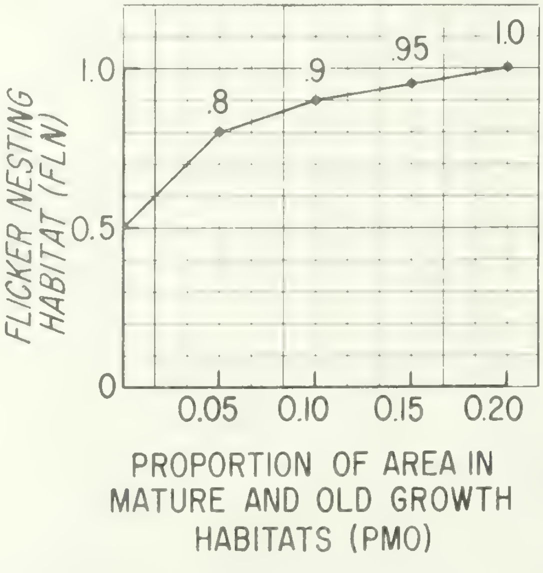

Figure 2.—Flicker nesting habitat versus the proportion of area in mature and old-growth habitats.

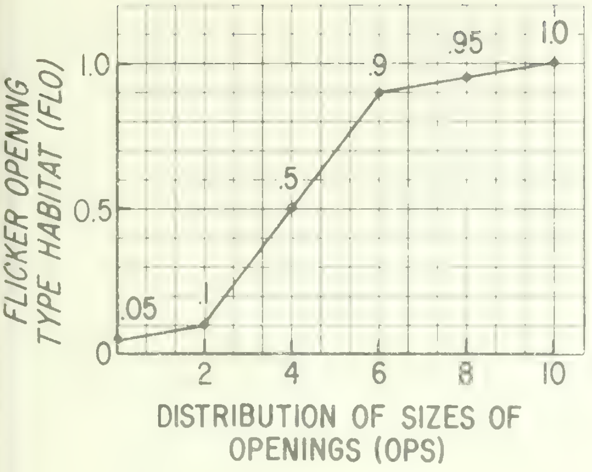

Figure 3.—Flicker opening-type habitat versus the opening-size distribution.

opportunities are related to the proportion of forest area in seedling habitat and the average area of each seedling habitat. Nesting and resting opportunities are related to the proportion of the forest that contains mature and old-growth timber habitats interspersed among the seedling, sapling, and pole stands. The analytic silviculture technique (Boyce 1977) can be used to find out how prospects for flicker woodpeckers might change as the different modes of forest management are applied.

As the proportions of seedling, old-growth, and mature timber habitats and the size of openings change over time, values for these relationships (figs. 1, 2, 3) are used to compute a relative change in the potential livelihood for flicker woodpeckers. The product of the relationships provides an index to the potential livelihood of flickers; the index value is between 0 and 1. For the example, a mode of management is used that brings the proportion of old-growth and mature timber to about 75 percent, limits seedling habitats to 2 percent of the forest, and limits size of openings to less than 0.1 ha. As the distribution of habitats is changed from the original inventory to that for the selected mode of management, the index for the relative livelihood of flickers is plotted, along with changes in the distribution of seedling, mature, and old-growth habitats (fig. 4). With such small openings for feeding and with such a small proportion of the forest in seedling stands, the index for the livelihood of flickers approaches 0.

In the same forest area, a mode of management that places about 4 percent of the area in seedling habitats, increases the size of openings to about 4 ha., and keeps 28 percent of the area in mature and old-growth habitats produces a far better environment for the flicker (fig. 5). As we bring the organization of the forest to a steady state with this mode of management, the potential livelihood of flickers increases to about 75 percent of the maximum.

If one chooses, benefits of special interest may be plotted rather than the distribution of habitats (fig. 6). Various modes of management can be explored until a mode is found that results in a desirable joint occurrence of the desirable benefits. Other practical examples are illustrated elsewhere (Boyce 1977, 1978). If the mode of management is used long enough—about 100 years—to bring the organization of the forest to a steady state, this particular combination of benefits should be available for many centuries.

The validity of the mode of management and the analytic silviculture technique is dependent on the logic and validity of the four bionomic theories.

THE LOGIC OF THE THEORIES

The theories are based on existing knowledge and are not new. What is new is the formalization, in four concise statements, of large amounts of empirical knowledge about benefits and organisms in forests and the application of these formal statements to the systematic management of forests for multiple benefits. The logic for the theories is based on observed phenomena and reasoning for: (1) control and communication in individual organisms and in communities; (2) the delay and dissipation of energy and materials in forests; (3) the livelihood of endemic species; and (4) the congruence of the theories and the forest.

CONTROL AND COMMUNICATION IN THE ORGANISM AND THE COMMUNITY

Organisms represent kinds of systems that are structured to be self-organizing. However, they do not respond repetitively in the same way to the same environmental change every time the change is encountered. For example, people react differently to a sudden, loud noise if it is expected than if it is unexpected; a person reacts differently to a pinprick when alert than when anesthetized. Plants respond to a rapid decrease in temperature in relation to the preceding temperature regime. Organisms have parts connected by physical

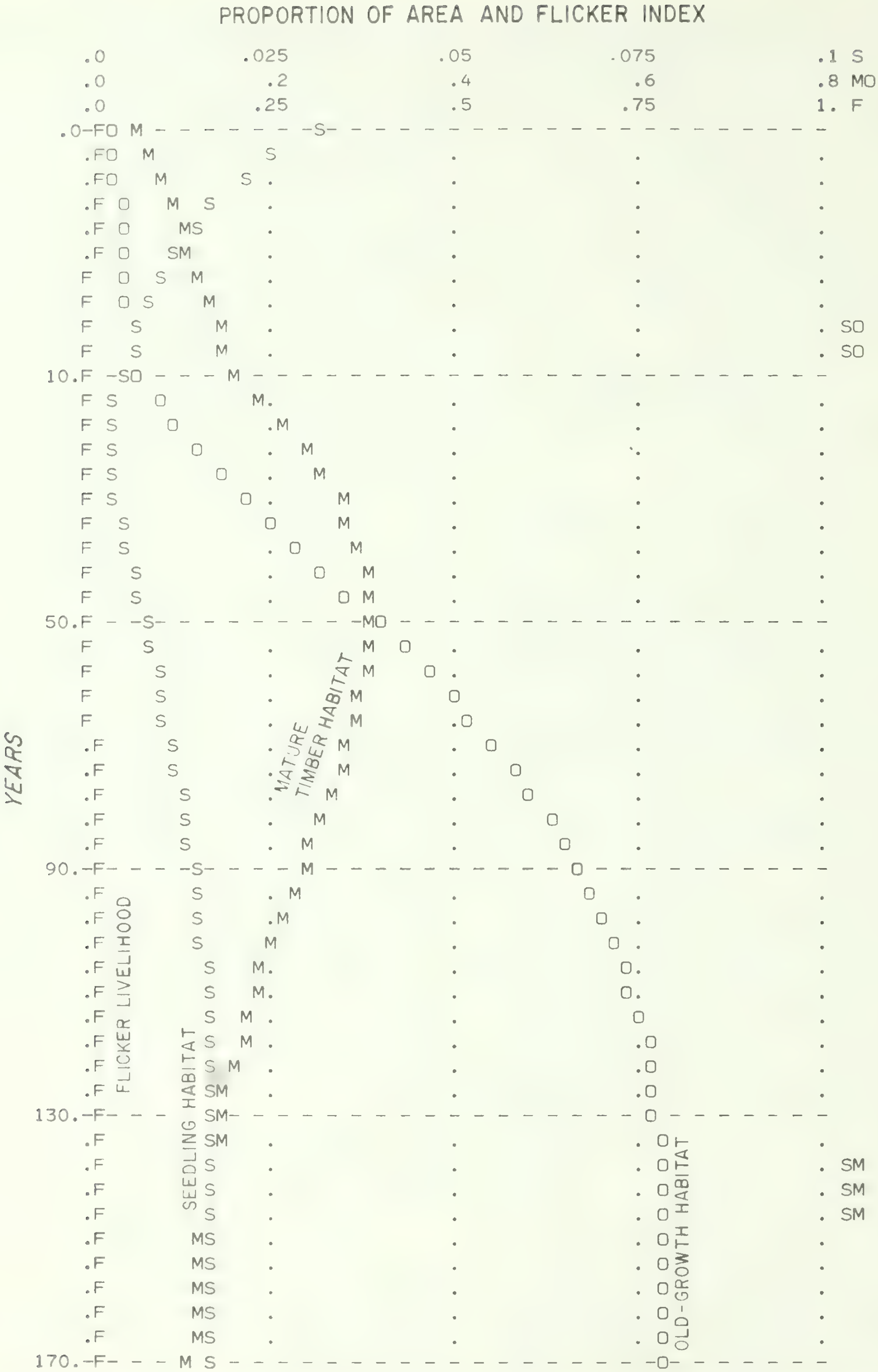

Figure 4.—The relative livelihood of flicker woodpeckers (F) in relation to changes in the proportion of old-growth, mature timber, and seedling habitats with 0.1 ha. openings over a period of time.

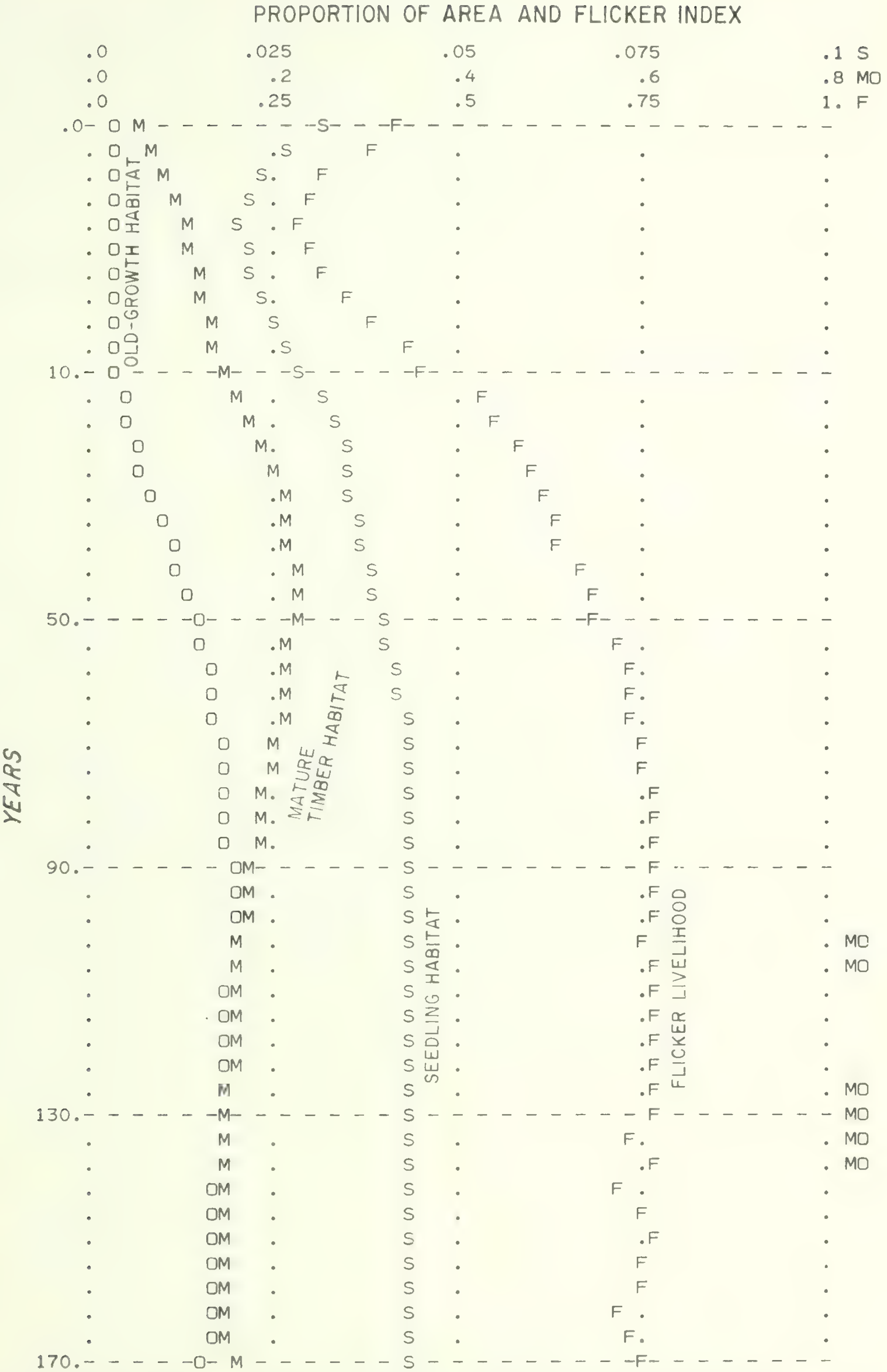

Figure 5.—The relative livelihood of flicker woodpeckers (F) in relation to changes in the proportion of old-growth, mature timber, and seedling habitats with 4 ha. openings.

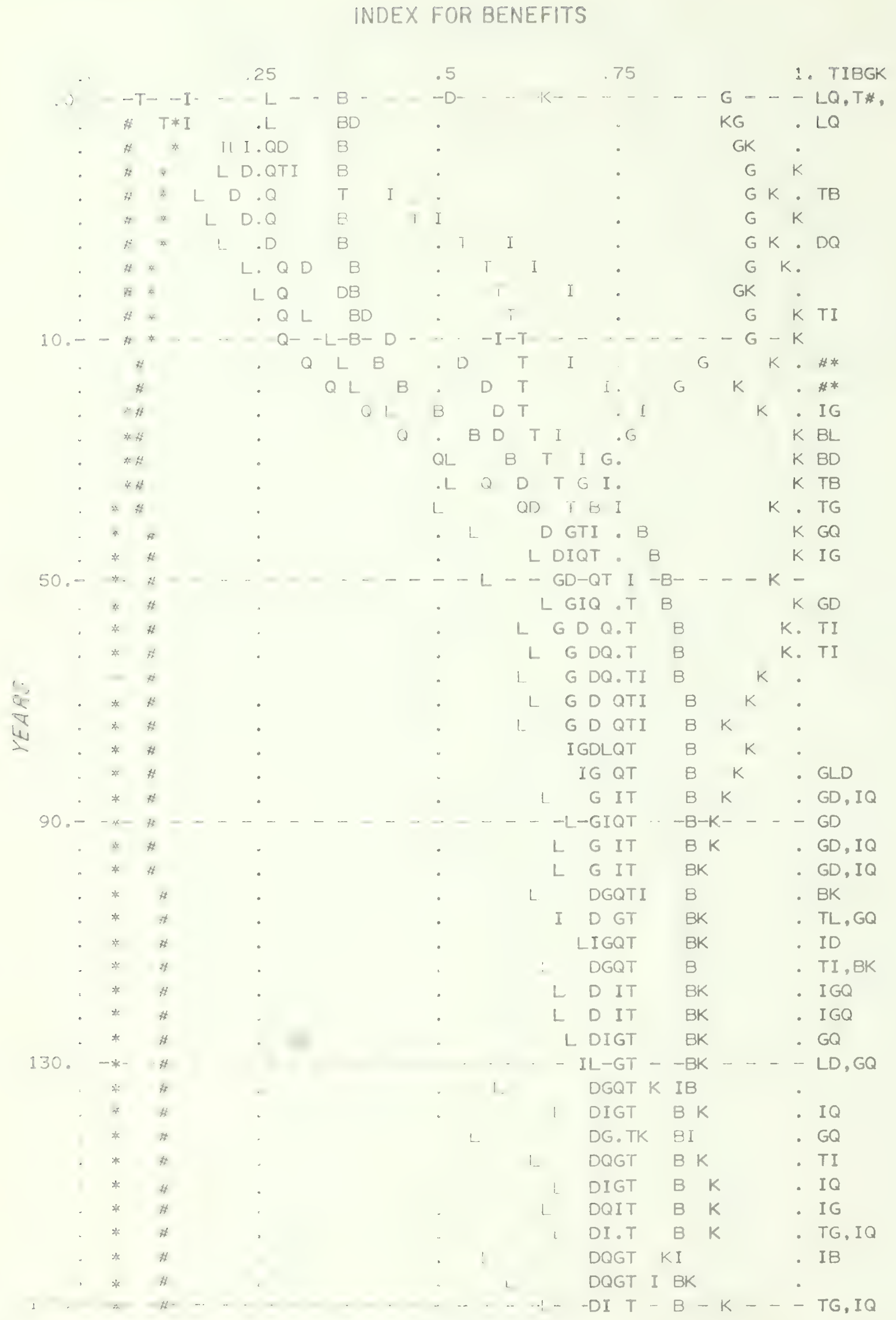

Figure 6.—Indices for eight benefits and one impact for one mode of management. T = potential timber index; I = sediment; B = bear habitat; D = deer habitat; Q = squirrel habitat; L = bluebird habitat; G = grouse habitat; K = turkey habitat; and # = water yield. The * is constraint quantum, discussed later in the text. Modified from figure 2 (Boyce 1977). Indices are plotted annually for the first 10 years, then at 4-year intervals. Letter groups at the top of the graph indicate coincident indices; the first letter of each group appears on the plot.

channels that transmit, in the form of energy and matter, information to direct the responses of the system in relation to the state of the system.

In contrast, other systems are deterministic. For example, a watch responds repetitively to the same environmental change, such as winding and setting, every time the change occurs. The parts of a watch are connected to transmit, in the form of energy and matter, the same information the same way every time. It cannot sense when it is keeping incorrect time and make corrections. The system, therefore, is deterministic because the structure does not include decision mechanisms to change the information.

Decision mechanisms in organisms include not only the central nervous system in higher animals, but also anatomy, physiology, and genetic mechanisms. Decision mechanisms are observed in both single (Koshland 1977) and multicelled organisms (Horridge 1977). The decision procedures are mechanical or chemical. The evidence is that organisms have the capability to change behavior in relation to the goal for survival. These decision mechanisms are explained by cybernetic concepts described and illustrated by Wiener (1948); Ashby (1973); Forrester (1961); Beer (1966); Milsum (1966); Klir (1969); Robinson and Knight (1972); Becht (1974); Kogan (1975); George (1977); and others.

Self-organizing systems contain decision mechanisms that use information to direct responses toward a goal. The communication channels form a loop that includes sensors, one or more decision mechanisms, and effectors. Since responses are periodically reversed to bring the organism to the state represented by a goal, these kinds of loops are called negative feedback loops. Organisms respond, behave, have the dynamics of systems with negative feedback loops.

A stylized diagram (fig. 7) illustrates the cybernetic concept of negative feedback loops without describing the enormous complexity in the individual organism. The state of an individual organism is represented by a rectangle. The state of the system is sensed and transmitted through physical channels, indicated by broken lines, to a decision mechanism illustrated by a circle in the diagram. Decision mechanisms, sensors, and physical information carriers in organisms include membranes in single cells, chemical compounds, and physical structure. Effectors (arrows on the diagram) include muscles, membranes, biochemical reactions, the movements of water, the transfer of ions, and the movement of cells.

The decision mechanism decides what is to follow in relation to a goal that is built into the organism by genetics, physiology, and anatomy. The overall goal, a line in the diagram (fig. 8), that is built into all organisms is survival. This goal is, of course, composed of many different subgoals and feedback loops. Examples are the negative feedback loops that maintain levels of blood sugar, balance in animals, and opening and closure of stomata in plants. Organisms without the overall goal of survival obviously do not live long enough to play significant roles in structure of communities, in reproduction, and in evolution (Simpson 1969; Stebbins 1974; Dobzhansky and others 1977). Failure of only one of the essential feedback loops results in mortality. "Correct" decisions are those that change the state of the organism to maintain life. Decisions result in

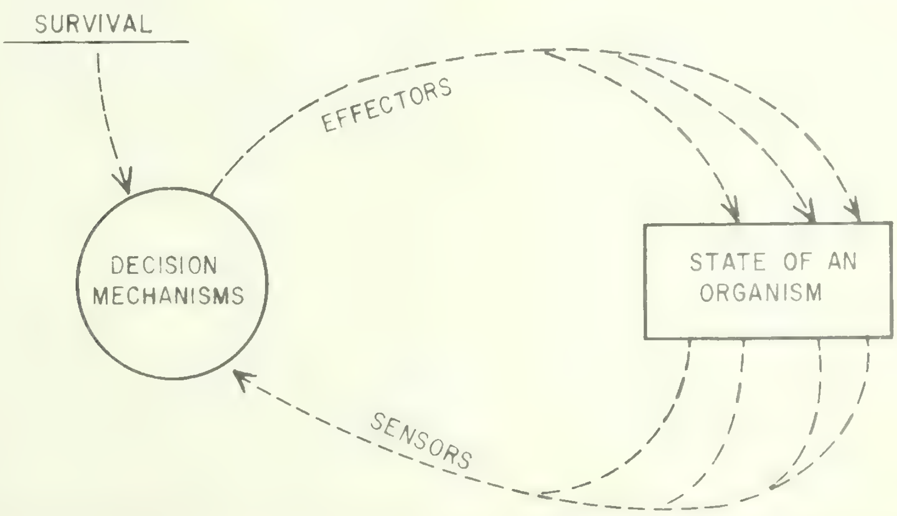

Figure 7.—A stylized diagram illustrating the cybernetic concept of negative feedback loops. See the text for an explanation.

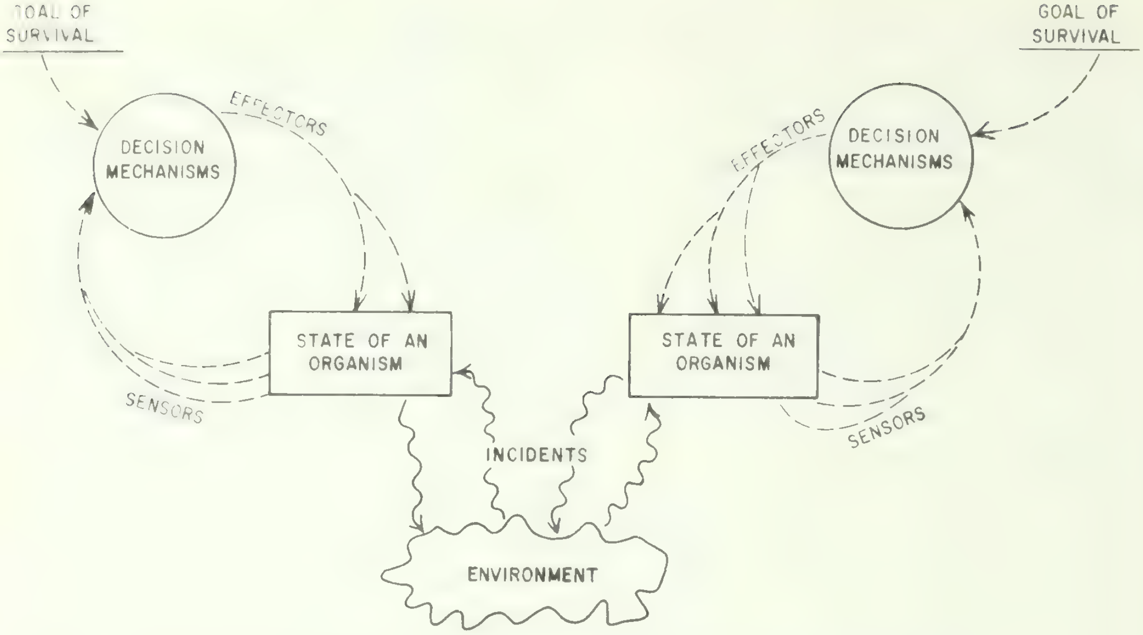

Figure 8.—This generalized diagram illustrates the way the component parts of organisms and their special environment are connected by communication channels.

many kinds of actions, such as movement from irritating substances, feeding, a change in electropotential of a membrane, and the opening of stomata in leaves. Most decisions for survival are determined not by crises, such as escaping from a predator, but by goals to maintain essential variables, such as the concentration of salt in the blood or the amount of water in leaves, within the limits for life.

Decision and control between two closely arranged organisms and both responding to the same factors of the environment (fig. 8) can now be examined. The environment, represented in the diagram by a many-faceted form, directly affects the state of each organism and indirectly, the kinds of decisions. Changes in environmental factors such as light intensity, day length, ions around a plant root, and temperature change the state of the organism. When the physical source of information that affects the decision mechanism is changed, the effect is always a change in the state of the organism. Removing one's finger from a hot stove immediately rather than waiting until the state of the environment is changed from "hot" to "cool" is an example of how physical information affects change in the organism. The environment is not a part of the negative feedback loops, but the environment may be changed by behavior of the organisms.

The environment is changed incidentally to the behavior of the organisms. There is no evidence that trees lose their leaves in order to maintain some amount of organic matter and nutrients in the soil. Stomata open and close in relation to the state of the plant and not to maintain some amount of water, oxygen, and carbon dioxide in the surrounding air. Conversely, the amounts of organic matter and nutrients in the soil and the amounts of oxygen in the air are unplanned consequences of the states of the organisms. One could add bird nests, termite nests, and other stuctures built by organisms. In the diagram (fig. 8) the lines connecting the organism and the environment are wavy to indicate the unplanned effects of each on the other. This kind of dynamic change by organisms is self-organization; that is, to self-organize by changing the chemical and physical conditions of the organism to maintain essential variables within the limits of life. Thus, organisms do not always respond in the same way to the same environmental change every time the environmental change is encountered.

Some components of environments such as heat, water, and oxygen seem to influence all organisms. Other elements may be factors in the environment for only certain organisms. Whether or not the element is an environmental factor depends on the physical and chemical structure of individual organisms. For example, colorblind people respond differently to wave lengths of light from others with normal sight. Some people respond differently from other people to contact with certain plants (poison ivy, *Rhus radicans* L.). Sharks and related animals respond to low frequency, feeble, voltage gradients that are not detected by other organisms (Kalmijn 1971, 1977). Certain wave lengths and periods of radiation are environmental factors for some organisms but not for others. Each organism and its special environment is different from every other organism and its special environment.

In the words of Tansley (1935): "Though the organisms may claim our primary interest, . . . we cannot separate them from their special environment, with which they form one physical system." Each organism and its inseparable and special environment is viewed as an individualistic system that is uniquely different from all other individualistic systems. And, the states of these systems change with migration, age of the organism, and changes in the organism's environment. For example, a bird in an open field forms a different individualistic system from that formed by the same bird in a forest.

Boundaries of the individualistic systems are determined by the physical limits of each environmental factor that is a part of the system. For example, heat may flow from inside the organism to a nearby sink or to the organism from a source. Spatially, the heat factor may extend to the sun. When a bird moves from an open fiield to a forest, the state of the individualistic system changes because both the intensity and the kinds of environmental factors that affect the state of the bird are different. When trees are moved to different environments, behavior of the trees cannot be predicted. However, the properties of the old and new environment may be used to explain why the trees behaved differently in different environments. Numerous examples are given by Dorman (1976) and Wright (1976). Also, it is extremely difficult to duplicate in controlled environments the behavior of plants grown in nature (Downs and Hellmers 1975). A well-known technique of biology is to use properties of an environment to explain the observed behavior of organisms in that environment. But the behavior of an organism introduced into a new environment is not to be deduced from the properties of that environment. In the new environment, the organism forms a different individualistic system from that formed in the previous environment.

The first theory and the related logic supports the second theory.

Assemblies of individualistic systems are viewed as communities (Gleason 1939). Communities are not a random assortment of all kinds of genotypes that attempted to survive in a given area. Rather, the vertical and horizontal distributions of plants and animals are ordered. Once observed, certain generalizations can be made about the probable order of plants and animals in a community. For example, the succession of plant species on retired cropland in the Southeastern United States (Oosting 1956) can be described from repetitive observations. But the organization over time could not be deduced from the properties of the environment and knowledge of the plants in adjacent natural communities. Enormous numbers of different kinds of genotypes enter retired croplands from adjacent communities, but only a relatively few kinds survive at any one time. Succession is a sequence of states of organization and often becomes a series of relatively stable zones of different species. This latter kind of organization is evident in many coastal areas (Art 1976). Mortality thus organizes the different genotypes into uniform communities, zones of species, the observed stages of succession on retired cropland, and the dynamic changes following the harvest of trees.

When a hectare of forest is harvested and a new stand regenerates from sprouts and seedlings, the new stand passes through successive states of organization. The succession of states results from the mortality of individualistic systems, many of which were in existence at the time the new stand originated (Sander and Clark 1971; Marquis 1975). For the next 100 and more years, changes in the organization of a stand occur by the mortality of individualistic systems. Mortality may be related to storms, fire, silviculture, or other changes in the environment, but the environment does not select individuals to die or survive. The meaning of the phrase "environmental selection" is that one or more feedback loops in some individualistic systems fail to maintain some essential variable within the limits of life. Thus, mortality and the resulting organization of communities result from failures of mechanisms within individualistic systems rather than from discrimination by the environment (Dobzhansky and others 1977).

During the 100-year life of dominant trees in a forest, millions of seeds and other propagules die. This organizing mechanism for communities is different from that of individualistic systems. Communities have no physical channels of communication that link the individualistic systems to a decision mechanism. There is, therefore, no goal for the forest by which some centralized decision mechanism decides which species are to survive and which ones are to die. There is no goal for a certain association and distribution of species. Thus, there cannot be natural steady states, equilibriums, or climax forests. As Simpson (1969) indicated, during 3.5 billion years there is no paleontological evidence for natural stabilization or static equilibrium of communities.

Individualistic systems in a community are linked only through the environment (fig. 8) and not through a communication network to a decision mechanism that coordinates behavior, survival, and mortality. This is true for parasites, mycorrhizae, symbiotic organisms, and social insects. In social insects, odors, behavior, and other forms of communication are factors in the environment of individuals. Coordinated behavior results from similarities in genotypes responding to similar environments.

The second theory simply describes order in natural communities as resulting from the mortality of individualistic systems. Mortality results from failure of the individualistic systems to maintain some essential variable within the limits of life. The dynamics of this organizing mechanism for communities are similar to those systems without feedback loops.

THE DELAY AND THE DISSIPATION OF ENERGY AND MATERIALS

The delay and the dissipation of energy and materials by organisms is not easily explained by the theories of equilibrium thermodynamics. The difficulty is well stated by Spanner (1964). In an epilog to his book he notes that life as we know it is always associated with the delay and the dissipation of matter and energy, the two entities with which the second law of thermodynamics is concerned at equilibrium conditions. Then he points out that every aspect of life, after all, turns on the existence of a lack of equilibrium; for instance, the ability to see presupposed nonequilibrium between the radiation which the eye is emitting and the radiation entering it from the outside. He observed that if the universe is moving inevitably toward thermodynamic equilibrium, then as far as the biologist is concerned, that means death to all organisms.

Biological processes lead in time to evolution, migration, and extinction of different forms of life without genetic and environmental stability (Simpson 1969; Spurr and Barnes 1973; Dobzhansky and others 1977). A new stand of trees is not usually a repetition of preceding forest stands, although repetitive stands may be physically classified as seedlings, saplings, poles, mature timber, and old growth. The probability that environments and species will be repetitive for two consecutive 100- to 300-year periods is remote. The probability that newly established seedlings will have the same genotypes as the dominant trees is remote. Also, the distribution of genotypes changes with fluctuations in mortality as the stands transform from seedling to old-growth states of forest organization (Boyce and Cost 1978).

Phenomena which do not pass through successive equilibrium states are considered in studies of nonequilibrium thermodynamics. This area of investigation is also called the thermodynamics of irreversible processes (Wisniewski, Staniszewski, and Szymanik 1976). Nonequilibrium phenomena were observed in the early 1850's, but it was not until Onsager formulated his principle of microscopic reversibility that much progress was made in developing modern nonequilibrium thermodynamics. For additional information, one may wish to examine the work of de Groot and Mazur (1969). This paper relies on the monographs by Glansdorff and Prigogine (1971) and Nicolis and Prigogine (1977) for most of the ideas applied to the nonequilibrium states of forests.

If the amount of living biomass comes to some steady state, then the elemental outputs of energy and materials equal elemental inputs. This is described in more detail by Vitousek and Reiners (1975). One observes that natural mortality and the harvest of trees temporarily increase rates of flows of water, nutrients, and energy. As stands succeed to the old-age state of organization, increased rates of mortality result in increased flows of energy and materials. Various forms of perturbation, such as storms, insects, diseases, fire, silviculture, and harvest of timber, increase the rates of mortality. The result is to speed the transformation of the forest through a series of successive new states.

If a relatively small opening is formed in a forest by removing a single, codominant tree, little or no seedling growth occurs and few or no new propagules are established or increase in growth rate. An understory seedling or sapling does not increase its growth rate and rapidly fill the space left by removal of the tree. Rather, surrounding trees increase in growth until their crowns and roots fill the vacated space (Roach and Gingrich 1968). The forest has not returned to the previous state but has shifted to a new state.

The mortality of groups of contiguous trees creates relatively large openings. The sprouts and seedlings in the understory, in this case, begin to grow rapidly, although most eventually die. New propagules are established but most of them die. Mortality accentuates the fluctuations. Survivors continue to grow, often at an increased rate. The result is the transformation of the stands from one state of species composition and distribution of number and size of individuals to succeeding states of organization.

In both of the preceding observations, which are well known in the practice of forestry, there is no reversal in the species composition, distribution of individuals, and other states of organization. Nonequilibrium conditions resulting from mortality lead to unidirectional flows of energy and materials. The flows through the forest community are dissipative rather than conservative and are toward increased entropy of the universe. For example, in many plants, ions often move from leaves to the stems before the leaves fall. But, this movement of ions within the plant is not determined by the plant sensing the availability of ions in the environment. The negative feedback loops function within the organism to maintain certain variables, such as ion concentrations, within certain limits. There is no evidence for communication channels and decision mechanisms that increase the rate of ion uptake from the soil as concentrations of ions in the soil decline. And, there is no evidence that plants release ions to regulate ion concentrations in the soil. Ions accumulated by organisms are dissipated in many ways, including mortality. Thus, organisms delay and dissipate but do not regulate the flows of energy and materials through the land.

Organisms and communities of organisms which we call forests are irreversible systems constantly being transformed from one nonequilibrium state to another and never returning to a preceding state. Again, we find there can be no equilibrium state for a forest or a species. Some uthors (Simpson 1969; Dobzhansky and others 1977) estimate that 99 percent of all species that ever existed are extinct. As organisms evolve, migrate, and become extinct, the coexistent species that form a forest change over time. Changes n both environments and in genotypes over time cause each succeeding forest stand to differ from he preceding stands. Thus, the dynamics of orests may be readily understood and explained by the principles of nonequilibrium phenomena.

The third theory is simply a statement of observed phenomena that relates the behavior of organisms and communities to the thermodynamic principle of increasing entropy of the universe. Explanations are to be found in the principles of nonequilibrium thermodynamics for the unidirectional flows of energy and materials, and for the changes in the kinds of organisms and forests over time.

THE LIVELIHOOD OF ENDEMIC SPECIES

States of forest organization can be described in terms of the type, size, and condition of stands. One can first recognize stands of seedlings, saplings, poletimber, mature timber, and old growth, for example. Then one can include the areas of the stands, which are dependent on the size of openings formed by mortality and the harvest of timber. For convenience, we call these states habitats (Elton 1949).

Seedling stands provide for the livelihood of certain plants and animals that do not occur in older stands. Old stands provide for the livelihood of certain plants and animals that do not exist in younger stands. Yet, some organisms exist in all states of forest organization. Furthermore, the area of each stand influences the quality of the habitats for certain plants and animals. For a given forest area, the distribution and the areas of seedling, sapling, pole, mature, and old-growth stands determine the potential for a livelihood of most, if not all, endemic plants and animals.

From all the enormous numbers of different kinds of propagules that attempt survival, only a few live long enough to reproduce. This fact is clearly demonstrated by the distribution of organisms in relation to airborne salts near the oceans (Art 1976). Individualistic systems, by the fact of their survival, are adapted to all environmental changes over the period of survival. And, many of the mortal individuals are adapted to periods of environmental change that may be different from that of the surviving organisms (Stebbins 1974; Mayr 1970; Dobzhansky and others 1977). Thus, individuals of the same species opportunistically occupy ranges of temporal and spatial environmental gradients (Pickett 1976; Art 1976). The long time evolution and migration of a species is, therefore, dependent on some minimum number of propagules surviving and reproducing. This relatively small number of individuals transmits to their propagules genetic re-combinations from which develop individualistic systems, organism and environment, different from their parents. The important point for support of the theories is that differential survival and reproduction over time of a small fraction of genotypes and the recombination of genes provides for the livelihood of species in a spatially and dynamically changing environment.

It is readily apparent that nonequilibrium environmental conditions are conducive to the continued natural evolution of the largest number of endemic species. An environment highly constrained for uniformity in space and over time could limit the number of species and may speed the natural rates of extinction. But, neither environments nor organisms occur at random, nor do they occur independently of each other. There are too many species, too much variance in genotypes, and too many environmental factors to relate groups of organisms to sets of nonequilibrium environments. The nonequilibrium distribution of habitats can be expressed, however, in terms of an index of constraint from complete randomness. Such an index can be used to monitor the kinds and proportions of various states of organization. For management purposes, the constraint quantity would indicate how much one or more habitats were being favored over another. This situation would signal a possible loss in the livelihood of some organisms or other benefits.

A modification of a logarithmic expression that has been used in statistics (Fisher, Corbet, and Williams 1943), statistical mechanics (Tribus 1961), information theory (Shannon and Weaver 1949), and ecology (Pielou 1977) for many years can be used. The equation is modified to provide values, called constraint quanta (CQ), that vary between 0 and 1 (Boyce and Cost 1978).

$$CQ = \frac{\left(\sum_{i=1} p_i \cdot \ln p_i\right) + \ln N}{\ln N}$$

The percentage of the area (p) for each habitat is multiplied by the natural logarithm of the same value. These values are summed for all habitats. This sum is a negative value that is added to the natural logarithm of the total number of habitats (N) and divided by the same natural logarithm. The value of CQ approaches 0 when the distribution of the habitats is equal. The value of CQ approaches 1 when the distribution of habitats is constrained to favor one habitat over all others. Any biological or physical constraint that limits the number of classes of habitats, such as seedling, sapling, and old growth, or limits the random distribution of areas of habitats by classes, increases the value of CQ. Thus, an increase in CQ indicates an increasing constraint on the variety of habitats. The use of CQ is to indicate a reduced livelihood for some organisms and a reduced availability of some benefits. But, which organisms and which benefits are being constrained is not indicated by CQ.

There is no obvious optimum CQ. One can determine for a particular forest area a range of values for CQ that provides a livelihood for these organisms for which we have habitat requirements. The assumption is that a mode of management that favors a wide taxonomic group of organisms would provide the nonequilibrium conditions favorable for most endemic species. An example (fig. 6) illustrates these relationships.

In figure 6, CQ is plotted as an asterisk for the condition classes of the forest. The CQ value declines for about 40 years and then remains at about 0.05. CQ is not correlated with any of the benefits. The change in value simply indicates that this mode of management is changing the distribution of habitats towards less constraint. This change can be observed when the proportions of stand condition classes, seedlings (S), saplings (A), pole-6 (6), pole-8 (8), pole-10 (1), mature timber (M), and old growth (O), are plotted with the CQ values (fig. 9). For this forest area, CQ values of about 0.05 for habitats result in a certain combination of benefits being available at a relatively high rate (fig. 6). One can assume that the livelihood of many, if not most, endemic species is favored by this distribution of habitats. Thus, CQ has a monitoring value.

When a mode of management is considered that leaves the timber uncut (fig. 10), the proportion of old-growth habitat increases to about 63 percent of the area. The CQ value (*) remains below about 0.2 until year 30, then the constraint quanta increase to about 0.34 by year 110. The increase in constraint results from an increase in the proportion of area in old growth and in the reduction of area in seedling, sapling, and pole-sized stands. The proportions of areas in the younger habitats are constrained by the large area in old growth. The increasing constraint in the distribution of habitats is monitored by the increase in constraint quanta.

Since no timber is harvested, the potential timber yield (T) is 0 (fig. 11). The lack of timber harvest keeps the increased flow of water (#) very low. The small amount of browse due to small

PERCENTAGE OF AREA BY HABITATS AND CONSTRAINT QUANTA VALUES

YEARS

```
      .0                .1                .2                .3                .4 S
      .0                .2                .4                .6                .8 A681MO*
   .0- O MS- -8-*- -A- - -16 - - - - - - - - - - - - - - - - - - - - - - - - - -
     . O SM     8     A      6            .                 .                 . 61,8*
     . OS  M    8     A     6             .                 .                 . 61,8*
     . OS   M * 8  A.    61               .                 .                 .
     . OS    M* 8  A.   6 1               .                 .                 .
     . OS    M*  8 A.   6 1               .                 .                 .
     . OS     *M  8 A. 6 1                .                 .                 .
     . O S    *M  8 A.6  1                .                 .                 .
     . O S  *  M  8A.6   1                .                 .                 .
     . O S  *  M  8A6    1                .                 .                 .
   10.- O S -*- -M-8A - -1- - - - - - - - - - - - - - - - - - - - - - - - - -  A6
     .  O S*      M6A.   1                .                 .                 . 68
     .  O S*     6 8A.  1                 .                 .                 . 8M
     .   OS     6 8 A.  1                 .                 .                 . AM,S*
     .   OS    6  8 AM  1                 .                 .                 . S*
     .    S   6 8  A.M1                   .                 .                 . SO*
     .    SO  6 8   AM1                   .                 .                 . S*
     .   * SO6 8    A1                    .                 .                 . 1M
     .   * SO6 8    A1M                   .                 .                 .
     .   * S 68     A M                   .                 .                 . A1,6O
   50.- - * S 68- - -1AM- - - - - - - - - - - - - - - - - - - - - - - - - - -  8O
     .   * S 68     1.A                   .                 .                 . AM,8O
     .   * S 68O    1.A                   .                 .                 . AM
     .   * S 6 O  1 .MA                   .                 .                 . 68
     .  *  S 6 O  1 .MA                   .                 .                 . 68
     .  *  S 6  O 1 M A                   .                 .                 . 68
     .  *  S 6  O1  M A                   .                 .                 . 68
     .  *  S 6  O1 M.  A                  .                 .                 . 68
     .  *  S 86 O1 M.  A                  .                 .                 .
     .  *  S 86 O1 M.  A                  .                 .                 .
   90.- -*- -S86- 1M- - A - - - - - - - - - - - - - - - - - - - - - - - - - -  1O
     .  *   S 6  1M .  A                  .                 .                 . 68,1O
     .  *   S 6  1M .   A                 .                 .                 . 68,1O
     .  *   S 6  1  .   A                 .                 .                 . 68,1MO
     .  *   S 6  1  .   A                 .                 .                 . 68,1MO
     .  *   S 6 O1  .   A                 .                 .                 . 68,1M
     .  *   S 6 O1  .   A                 .                 .                 . 68,1M
     .  *  S  6 O1  .   A                 .                 .                 . 68,1M
     .  *  S  6 O1  .   A                 .                 .                 . 68,1M
     .  *  S  6 M1  .   A                 .                 .                 . 68,MO
  130.- -*- S -6-M1 - - -A- - - - - - - - - - - - - - - - - - - - - - - - - -  68,MO
     .  *  S  6 M1  .   A                 .                 .                 . 68.MO
     .  *  S  86M1  .   A                 .                 .                 . MO
     .  *  S  86M1  .   A                 .                 .                 . 6O
     .  *  S  86M1  .   A                 .                 .                 . 6O
     .  *  S  86M1  .   A                 .                 .                 . 6O
     .  *  S  86M1  .   A                 .                 .                 . 6O
     .  *  S   6M1  .   A                 .                 .                 . 68O
     .  *  S   6M1  .   A                 .                 .                 . 68O
     .  *  S   6M 1 .   A                 .                 .                 . 68O
  170.- -*- S -O6 M1- - -A- - - - - - - - - - - - - - - - - - - - - - - - - -  6
```

Figure 9.—The constraint quanta (*) of about 0.05 for habitats in this particular forest result in a certain combination of benefits being available at a relatively high rate. S = seedling habitat; A = sapling habitat; 6 = pole-6 habitat; 8 = pole-8 habitat; 1 = pole-10 habitat; M = mature timber habitat; O = old-growth habitat.

YEARS

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PERCENTAGE OF AREA BY HABITATS AND CONSTRAINT QUANTA VALUES

    .0             .1             .2             .3             .4 S
    .0             .2             .4             .6             .8 A681MO*
  .0- 0 MS- -8-*- -A- - -16 - - - - - - - - - - - - - - - - - - -
    . 0 SM    8    A     6        .              .              . 61,8*
    . 0S  M   8    A    6         .              .              . 61,8*
    .  S   M * 8  A.   61         .              .              . SO
    . SO    M* 8  A.  6 1         .              .              .
    . SO    M*  8 A.  6 1         .              .              .
    .S O    *M  8 A. 6 1          .              .              .
    .S O    * M 8A .6  1          .              .              .
    .S  O   *  M A .6  1          .              .              . A8
    .S  O   *  M A 6   1          .              .              . A8
 10.-S- O - * - A86 - -1- - - - - - - - - - - - - - - - - - - - - AM
    S     O*   A68M.   1          .              .              .
    S      O  A6 8 .M 1           .              .              . O*
    S      * A  8  .  1           .              .              . A6O,1M
    S       A  8   .  1M          .              .              . A6*,8O
    .S     A* 8  O . 1   M        .              .              . A6
    .S    A  *8    O1    M        .              .              . A6
    .S   6A  8*    .1O    M       .              .              .
    .S   A  8  *   1   O   M      .              .              . A6
    .S  6A 8    * 1.     O M      .              .              .
 50.-S- 6A8 - - -1- - - - -MO - - - - - - - - - - - - - - - - - - 1*
    .S  6A8     1 *.       M  O   .              .              .
    .S 6 A     1   *       M    O .              .              . A8
    .S 6 A    1    .*     M       O              .              . A8
    . S68A    1    . *    M       .O             .              .
    . S68A   1     .  *  M        .  O           .              .
    . S68A  1      .   * M        .    O         .              .
    . S6 A  1      .    M         .     O        .              . 68,M*
    . S6 A 1       .   M *        .       O      .              . 68
    . S6 A1        .  M   *       .        O     .              . 68
 90.- S6-A1 - - - - - M - * - - - - - - - - O - - - - - - - - - - 68
    . S6 A1        . M     *      .          O   .              . 68
    . S6 1A        .M       *     .           O  .              . 68
    . S6 1A        M        *     .            O .              . 68
    . S6 1A       M.        *     .             O.              . 68
    . S6 1A       M.         *    .             O.              . 68
    . S61 A      M .         *    .              O              . 68
    . S61 A      M .         *    .              .O             . 68
    .  S1  A    M  .         *    .              .O             . S68
    .  S1  A   M   .          *   .              .O             . S68
130.- -S1 -A- -M- - - - - - - * - - - - - - - - - O - - - - - - - S68
    .  S1  A   M   .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A M     .          *   .              . O            . S68
    .  S1  A M     .          *   .              . O            . S68
    .  S6  A M     .         *    .              . O            . S8,61
    .  S6  A M     .         *    .              . O            . S8,61
    .  S6  A M     .         *    .              . O            . S8,61
170 - -S6 - A - - - - - - - -*- - - - - - - - - - -O- - - - - - - S8,61,AM
```

Figure 10.—When no timber is harvested, the proportion of old-growth habitat (O) increases and constrains the amount of mature timber (M), poletimber (1, 8, 6), saplings (A), and seedlings (S). This constraint is indicated by the rise in constraint quanta (*).

YEARS

```
                          INDEX FOR BENEFITS

     .0            .25             .5            .75             1. TIBGKLDQ#
   .0T  -#- -*-  - - Q - - B - - - - D - - - - - - - G - - - - - - TIKL
     T   #   *      . Q    DB      .              .  G           . TIKL
     T   #   *     D.  Q     B     .              .  G           . TIKL
     T  #   *  D    .  Q     B     .              .  G           . TIKL
     T  #   * D     .   Q     B    .              .  G           . TIKL
     T  #   D       .    Q     B   .              .  G           . TIKL,D*
     T  #  D*       .     Q    B   .              .  G           . TIKL
     T #  D *       .       Q   B  .              .  G           . TIKL
     T # D *        .        Q  B  .              .  G           . TIKL
     T # D *        .         Q B  .              .  G           . TIKL
  10.T #D- * - - - - - - - - - -QB - - - - - - - - -G- - - - - - - TIKL
     T D   *        .             B.  Q           G              . TIKL,D#
     T D   *        .              .B         QG  .              . TIKL,D#
     T#D   *        .             B.       G    Q .              . TIKL
     T#D   *        .           B  .    G         Q              . TIKL
       T#D  *       .          B   .G             .Q             . TIKL
     T# D   *       .        BG    .              .  Q           . TIKL
     T# D    *      .    G  B      .              .     Q        . TIKL
     T#  D    *     . G     B      .              .         Q    . TIKL
     T#  D    *   G .      B       .              .            Q . TIKL
  50.T#- -D- - *G- - - - - B - - - - - - - - - - - - - - - - - - Q TIKL
     T#   D   G *   .     B        .              .              Q TIKL
     T#    D G   *  .     B        .              .              Q TIKL
     T #   D G    * .     B        .              .              Q TIKL
     T #   DG      *.      B       .              .              Q TIKL
     T #    G       *      B       .              .              Q TIKL,GD
     T #    G       *      B       .              .              Q TIKL,GD
     T #    GD      .*      B      .              .              Q TIKL
     T #    GD      . *     B      .              .             Q. TIKL
     T #   G D      . *     B      .              .           Q  . TIKL
  90.T # - -G-D- - - - * - -B- - - - - - - - - - - - - - - Q - - - TIKL
     T #    G D     .  *    B      .              .      Q       . TIKL
     T #    G D     .   *   B      .              .    Q         . TIKL
     T #    G D     .   *  B       .              .   Q          . TIKL
     T #    G  D    .    * B       .              .Q             . TIKL
     T #    G  D    .    *B        .            Q .              . TIKL
     T #    G  D    .    B         .          Q   .              . TIKL,B*
     T #    G  D    .    B         .        Q     .              . TIKL,B*
     T #     G D    .   B*         .      Q       .              . TIKL
     T #     G D    .  B *         .    Q         .              . TIKL
 130.T # - - G D - - - B-*- - - - - -  Q - - - - - - - - - - - - - TIKL
     T  #    G D    .  B  *        . Q            .              . TIKL
     T  #    G D    . B   *        .Q             .              . TIKL
     T  #    G D    . B   *        Q              .              . TIKL
     T  #     GD    . B   *        Q              .              . TIKL
     T  #     GD    . B  *        Q.              .              . TIKL
     T  #     G     .B   *        Q.              .              . TIKL,GD
     T  #     G     .B   *       Q .              .              . TIKL,GD
     T  #     G     .B   *       Q .              .              . TIKL,GD
     T  #     G     .B   *       Q .              .              . TIKL,GD
 170.T -#- - -G- - - -B- * - - - Q - - - - - - - - - - - - - - - - TIKL,GD
```

Figure 11.—When no timber (T) is harvested, some benefits such as water yield (#) and the livelihood for grouse (G), deer (D), bear (B), and in time squirrel (Q), are constrained. The relative amount of constraint of the habitats from complete randomness is indicated by the rising constraint quanta (*).

amounts of seedling habitats keeps the livelihood for deer (D) low. The livelihood of grouse (G) declines rapidly after the 10th year as the amount of old-growth timber increases. Black bear (B) livelihood increases for about 15 years, then declines. Squirrel (Q) increases to a maximum, then declines after year 80. The constraint quanta are not correlated with any of the benefits that are considered. However, the increase in CQ above about 0.2 indicates that the livelihood of some organisms is being constrained. One can assume that the livelihood of species other than those considered, possibly some spiders, songbirds, and small mammals, is also constrained. For these seven kinds of habitats in hardwood forests, like these in the Southern Appalachians, constraint quanta values greater than 0.2 suggest some kind of constraint on the livelihood of endemic species.

The fourth theory relates the opportunities for natural rates of evolution, migration, and extinction to the organization of habitats. Each combination of habitats has a particular combination of human benefits available, such as the harvest of timber, the flow of water, hunting opportunities, and a combination of places to live for endemic plants and animals. The distribution of habitats can be monitored with a dimensionless number, constraint quantum, that measures the relative amount of constraint from an even distribution.

CONGRUENCE OF THE THEORIES AND THE FOREST

Decisions are derived by forest managers from a mental model of the forest. The most important components of the mental model are the theories that serve to interrelate empirical data, and thereby reduce the complexity for deriving decisions. Management actions are effective when the theories in the mental model are congruent with the real forest. By congruent, it is meant that actions selected by the mental model direct the biological systems to achieve the desired state of forest organization. Congruence is assessed by challenging the theories with hypothesis for falsification and by the direct method of relating changes in macroscopic phenomena to management actions (Becht 1974; Popper 1962).

If a hypothesis for falsification is found to be true, the appropriate theory is falsified, or at least the theory and the hypothesis are to be reconsidered. Critical hypotheses for the four bionomic theories are:

1. The theory for individualistic systems is falsified by discovering that any individualistic system's existence, mortality, or behavior is for the exclusive achievement of a goal for the forest community. Proof of this hypothesis requires evidence for a centralized, community decision mechanism and communication channels to control and direct the behavior of each individual to benefit the community as a whole.

2. The theory for the organization of forests is falsified by discovery of a centralized community control and communication mechanism that senses the states of organization, makes decisions, and directs the mortality of organisms to achieve organizational goals for the forest community.

3. The theory for flows of energy and materials is falsified by discovery of centralized communication channels, sensors, and decision mechanisms in the community that permits the community as a whole to regulate the inflow, internal status, and outflow of energy and materials to achieve organizational goals for the forest community.

4. The theory for multiple benefits is falsified by discovery that all potential benefits and a livelihood for each endemic plant and animal are simultaneously available from a single state of community organization, i.e., all stand condition classes being in seedlings or old-growth habitat.

The direct method for maintaining congruence requires relating the theories to changes in macroscopic phenomena, such as reproduction, growth, and mortality. Predictions of the mental model are compared with changes in the real forest. Following the comparison, one either accepts, rejects, or modifies the theories. The direct method is traditional for practically all methods for forest management.

DISCUSSION

The four theories are a basis for the generalization that a natural, unmanaged forest is an aimless system. This is in agreement with the paleontological evidence for natural evolution, migration, and extinction of organisms. Management can convert this aimless system to a system with goals (fig. 12).

An information network is used to periodically inventory the state of the forest. Mental models of managers are the decision mechanisms and the goal is determined by the management objectives. Predictions and assessments are based on direct observation and measurement of macroscopic phenomena, such as growth, mortality, reproduction, and migration. This direct method is used in conventional forest management. The new directions differ from conventional forestry, primarily in the way goals are selected.

Traditional forest management is most successful when objectives are for one primary benefit such as timber, water, or a wildlife habitat, and other benefits are permitted to vary with the primary benefit. The difficulty, created by demands for multiple benefits, is to resolve conflicts in management actions when the objective is for two or more primary benefits. In determining economic, social, and biological goals, there is a major problem in translating goal statements into harmonized program actions. Since one can direct harmonized actions toward only one thing at a time, an obvious solution is to find a single goal toward which management actions can be directed. That goal, for the new direction, is a certain state of forest organization.

The organization of the forest (the distribution of habitats) is controlled by scheduling the rates of harvest and the size of openings formed by harvesting (Boyce 1977, 1978). Two or more rotation periods may be superimposed so that old growth and young stands are closely intermingled and, over time, interchangeable. Thus, age classes of stands are distributed in varying proportions from 1 year up to classes as old as 300 years. The distribution of habitats is brought to one of a large number of steady states. At any one of a number of steady states, a livelihood for most, if not all, endemic organisms is possible and certain combinations of benefits are available.

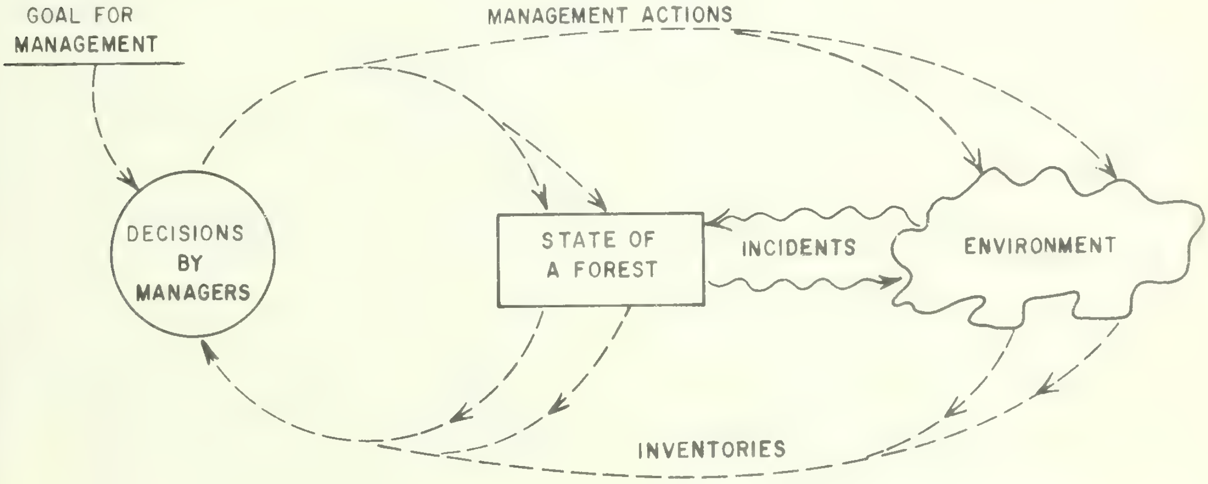

Figure 12.—This generalized diagram illustrates how forest management converts the aimless system for community organization to a system with goals.

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FOREST DIVERSITY—New Concepts and Applications

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Asheville, North Carolina

FOREST DIVERSITY—New Concepts and Applications

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Abstract.--The National Forest Management Act of 1976 requires that plans provide for the diversity of plant and animal communities to meet multiple-use objectives and, to the degree practicable, the preservation of tree species indigenous to particular forest regions.

The purpose of this paper is to define "diversity" as it applies to forest management and to discuss concepts relative to maintaining a desired stability of forest plant and animal life. Data presented support the contention that the monitoring of the natural succession of forest stands is useful for making management decisions, assuring diversity, and for keeping multiple-use objectives congruent with consumer attitudes for social and economic benefits.

KEYWORDS: Diversity, renewable resources, multiple-use, stability.

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1. INTRODUCTION

1.1 The Issues

Public concern for maintaining certain kinds of diversity in renewable resources is expressed in the National Forest Management Act of 1976 (90 Stat. 2949; 16USC1600). The Act requires that plans provide for the diversity of plant and animal communities to meet multiple-use objectives and specifies that steps be taken to preserve the diversity of existing tree species. To meet these provisions, the development of alternative management plans and definitions is necessary.

Forest managers have not previously defined diversity of renewable resources as an objective for management (Ford-Robertson 1971; Smith 1962; Forbes 1961), nor is there a useful definition in biological literature. Management for diversity to meet multiple-use objectives therefore is a new direction for forestry.

Obviously, the first requirement was to develop an operational definition for diversity of renewable resources. Section 2.1 provides this definition.

In section 2.2 we show how the diversity of renewable resources can be related to the availability of one or more benefits. In section 2.3 our analysis leads to the conclusion that increasing diversity of species does not beget stability of forest communities. In section 2.4 we illustrate how Shannon-type indices are confounded and, thus, cannot be used to develop relationships for use in management decisions. In section 2.5 we show how to monitor constraint in the distribution of habitats. And, we explain how constraint in the distribution of habitats may limit the livelihood for endemic species.

In section 3 we show how to compare the diversity of tree species in national forests and in a large surrounding region. The same method can be used for other parts of the Nation. We show that direct comparisons of lists of species, and possibly some other elements such as diameter class, are useful for management decisions.

In section 4 we use lists of forest types by stand condition classes to illustrate methods for direct comparisons of the diversity of plant and animal communities. We also illustrate ways to anticipate changes in the diversity of communities with different modes of management and changes under natural forces unaffected by man.

In section 5 we illustrate how diversity and benefits may be integrated to simultaneously analyze, estimate, and specify the consequences of alternative plans for multiple benefits. We describe how diversity is monitored and how data from periodic inventories can be used to keep multiple-use objectives congruent with consumer attitudes toward social and economic benefits from forests.

2. DEFINITION, CONCEPTS, AND THE SHANNON-TYPE OF DIVERSITY INDICES

2.1 An Operational Definition for the Diversity of Renewable Resources

The kinds of coexistent animals, plants, and microorganisms vary within and among forest stands. As time progresses, these renewable resources change in kind and in relative proportions from place to place. These variations are recognized as "diversity," which is the condition of being different. The classification, measurement, and control of the elements that make up diversity of forests and ranges are activities associated with managing renewable resources. It is the proportional distribution of diverse situations, such as different combinations of species and different habitats, that determines the availability of timber, wildlife, range production, recreation, streamflow, esthetics, and other benefits (Boyce 1977, 1978; Siderits and Radtke 1977; Flood and others 1977).

The development and the maintenance of certain differences among forest stands is an important principle for managing forests. For example, forest animals require various kinds and combinations of stand conditions in all seasons. The greater the difference, the greater is the opportunity for food and shelter (U.S. Dep. Agric., Forest Service 1971). For an increased flow of water without excessive sediment, the management technique is to establish a variety of age classes of stands (Douglass and Swank 1976). A sustained harvest of timber is also based on maintaining different age classes from regeneration to harvest (Smith 1962).

Classification, mensuration, and statistical sampling techniques have been developed to distinguish and measure meaningful differences in the elements of communities (Forbes 1961; Husch and others 1972). These elements include species of trees, forest types, animal and plant populations, volumes of timber, amounts of browse and hard mast, age classes of stands, site index, and stand condition classes (U.S. Dep. Agric., Forest Service 1967). Thus, these differences, which are viewed as diversity of renewable resources, are operationally defined. Criteria are specified so that one species of animal can be consistently distinguished from another; continuums, such as tree diameters and stand conditions, can be separated into meaningful classes; and whether some observed difference is meaningful for management decisions can be statistically determined.

An operational definition of the diversity of renewable resources is, in brief, the meaningful differences in the elements of biological communities.

The operational criteria are:

a. Identify which elements of the community are being considered (i.e., tree species, bird species, forest types, stand conditions, age classes).

b. Specify measurements or characteristics which evaluate or distinguish elements (i.e., differences between species, measurements for classes of a continuum).

c. Describe how the differences between elements are meaningful for management decisions (i.e., stand condition classes and the livelihood for a plant or animal, sizes of trees, and the potential for wood products).

Our definition of "diversity" is essentially the same as provided in most dictionaries. Thus, we are not proposing an uncommon meaning. The operational criteria provide the scientific basis for different people to repeat observations and measurements and, thus, provide scientific credibility for management decisions (Bridgman 1927).

2.2 The Relation of Diversity to Benefits

In this section we illustrate how diversity of elements of renewable resources can be related to the availability of one or more benefits. Such relationships are useful for considering alternative management plans and for choosing management actions. A well-known concept for providing a timber benefit is used to illustrate the relation of diversity of resources to a benefit.

Timber can be harvested only from stands that have trees large enough to meet a definition for timber. We define "timber" as trees 11 inches d.b.h. and larger and define a mature timber stand as one with half of the dominant and codominant trees qualifying as timber. If one has a forest with no timber, no timber benefits can be derived immediately. If all the stands in the forest are mature, the maximum timber benefit can be achieved in the shortest time. However, if one wants an annual timber benefit over a long period of time, then it is necessary to bring about a diversity of age classes and areas for each stand (Smith 1962). If one chooses the difference in the age classes to be 1 year, then the maximum area of stands for each age class equals the forest area divided by the time required for stands to become mature. Other diverse combinations are possible.

The diversity of stand area and age classes provides benefits other than timber. For example, a certain amount of livelihood for deer is provided by browse in the seedling years, by some hard mast as the stands approach maturity, and by cover in the sapling years (U.S. Dep. Agric., Forest Service 1971). During the seedling years the proportions of certain kinds of spiders increase, and as the stands age, the proportions of other kinds of spiders increase (Coyle, In press). If the diversity of annual age classes is changed, the timber benefit, as well as the potential livelihood for deer, the species of spiders, and other benefits will change. It is the state of organization of the forest (in this example the diversity of annual age classes) that determines the availability of multiple benefits.

This example illustrates one way diversity of specified elements of renewable resources can be used to make management decisions about the availability of specified benefits. It also illustrates the theory for multiple benefits, i.e., "the kinds and proportions of states of organization (habitats) determine the kinds and proportions of human benefits available from a forest" (Boyce 1977).

We can now consider how a reduction in the proportion of habitats reduces the availability of benefits. Consider first a random distribution of 80 age classes, each differing by 1 year. Such a distribution can be maintained by regulating the rate of harvest and the size of openings. Without a scheduled harvest and opening size, the larger trees increase in size and constrain both the size of openings and the proportion of stands in the younger age classes. In time the younger stands represent less of the forests. Correspondingly, benefits related to stands in the younger age classes decline, affecting the diversity of habitats.

Now, if we take appropriate action to increase the size of stands and the proportion of stands in the younger age classes, both the diversity of habitats and the availability of certain benefits increase. Not only can timber be harvested periodically, but also a livelihood is provided for an increased number of species. From Coyle's (In press) research, we can expect to provide a livelihood for the largest number of species when all of the 1-year age classes are present. This leads us to another useful concept about diversity: an increase in the diversity of habitats increases the potential livelihood for diverse kinds of organisms.

Much of the evidence for this concept comes from studies of the evolution, migration, and extinction of plants and animals. As illustrated by numerous examples (Dobzhansky and others 1977; Mayr 1970; Harper 1977; Stebbins 1950, 1974), regions having many different kinds of habitats are more likely to have greater diversity of genotypes than regions with a few kinds of habitats. This fact is supported also by evidence that organisms with chromosomal variations are more likely to survive in transition areas between different habitats than in a large uniform habitat. This concept is used as a basic principle in the evaluation of habitats for wildlife (Hair, In press; Siderits and Radtke 1977; Flood and others 1977). If one is dealing with a specific species and certain habitat requirements are known, then the operational criteria for diversity can be specified.

Consider, for example, deer in a hardwood forest in the Southern Appalachians. In this forest the habitat value for deer is high when many seedling stands are interspersed in an area which has substantial stands of large pole and mature sawtimber. Seedling stands contribute soft mast and forage, while 10-inch poletimber and mature timber are producers of hard mast. The livelihood for deer rises as the proportion of area in seedling habitat increases up to about 7 percent of the total area and as mast-producing timber increases to about 20 percent of the area. These are assumed to be optimum proportions within the practical limitations of multiple-use management. Deer often use seedling browse more effectively when it occurs in openings less than 10 acres in size. As the opening size increases beyond about 30 acres, the utilization of the forage declines.

These relationships, which indicate diversity in the components of deer habitat, can be expressed in relatively simple charts (figs. 1, 2, and 3). On the

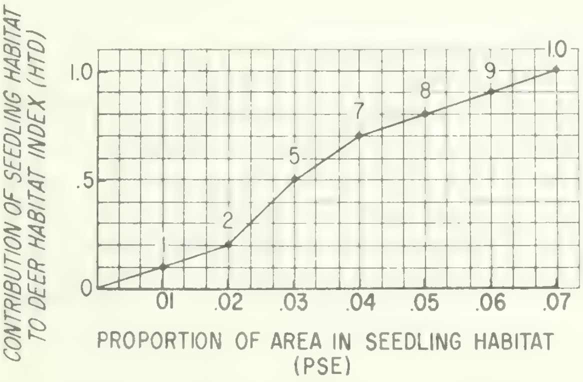

Figure 1.--Seedling habitats contribute soft mast and forage for deer (Boyce 1977).

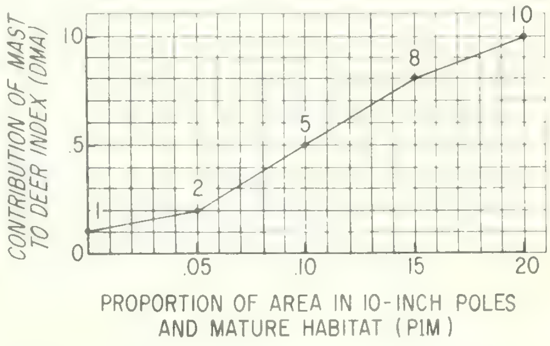

Figure 2.--Ten-inch pole and mature timber stands contribute hard mast for deer (Boyce 1977).

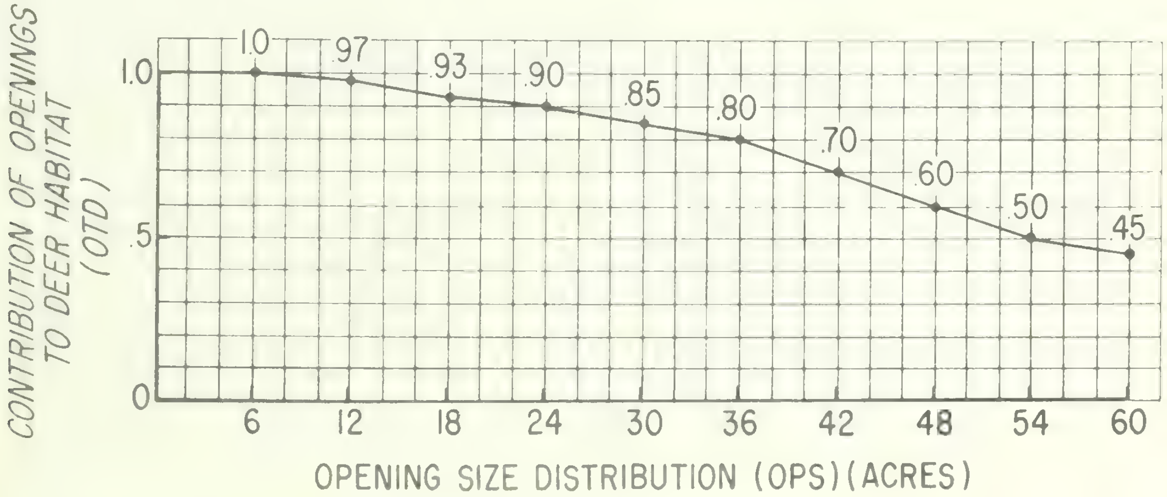

Figure 3.--Deer often use seedling browse more effectively when it occurs in openings of less than 10 acres (Boyce 1977).

verticle axis, the relative livelihood for deer is indicated by a scale of 0 to 1. For these examples, the product of the values that indicate the amount of browse, the amount of hard mast, and the size of openings, gives a combined index for some specific area. The diversity of forest elements, in this case the proportion of area in seedlings, large pole and mature timber, and opening size, can be used by forest managers to decide how alternative management actions may affect the livelihood for deer.

When one is dealing with a large number of species and an infinite number of differences in habitats, it is impractical to attempt to specify the operational criteria for each situation. One then relies on the concept that an increased diversity of habitats increases the potential livelihood for diverse kinds of organisms. A quantitative way to relate this concept to alternative management actions is discussed in section 2.5.

We use timber and wildlife benefits as illustrations, because the examples are widely known. The methods are readily applicable to esthetic, social, economic, and other benefits for which the elements of forest communities can be related. Thus, by knowing how management actions change diversity in the elements of forest communities, one can compare the consequences of alternative management plans.

2.3 Diversity of Species Does Not Add to the Stability of Communities

In this section we review the widely published concept that increasing diversity of species in communities begets stability. It is essential that we analyze this concept because it is often used to interpret consequences of actions to manage renewable resources (Cody and Diamond 1975; van Dobben and Lowe-McConnell 1975). Our analysis leads to the conclusion that unmanaged forests are nonequilibrium, aimless systems in which the diversity of species is a consequence of the dynamics of individualistic systems (Boyce, In press). We find no substantial evidence that increasing diversity of species begets stability of forest communities.

At the First International Congress for Ecology (van Dobben and Lowe-McConnell 1975), a primary concern was whether diversity of species contributed to stability of ecosystems. This meeting continued discussions that began in the late 1800's. Early studies of plant and animal species suggested slow rates of speciation and extinction and suggested that evolution increased diversity of species. A concept, not accepted by all biologists, was that the drift of evolution was toward diversity and complexity of individuals, which eventually resulted in relative stability in both the numbers of species and individuals (Watt 1966). Recently, the concept has been revived and there is widespread interest in diversity and the stability of communities.

In the literature the word "diversity" is frequently confused with the phrase "diversity index." Authors often define diversity by a mathematical expression that is a diversity index (Pielou 1977). Squiers and Wistendahl (1977) and [illegible] (1977) distinguished between diversity as difference and diversity index as a dimensionless number. Harper (1977) uses diversity as difference and [illegible] use diversity index. Odum (1971), Whittaker (1972), Pielou (1977), Peet (1974), and Auclair and Goff (1971) seem to use diversity and diversity index interchangeably. May (1976, page 158) argues for describing communities in terms of the elements of diversity rather than condensing information into diversity indices.

In his book on geographical ecology, MacArthur (1972) discusses the principle of community stability in some detail, presents a theory of species diversity, and develops a formula for indicating the amount of diversity in species. In a recent book dedicated to Robert MacArthur (Cody and Diamond 1975), a number of ecologists discuss the various concepts of diversity. One of the concepts propounded by MacArthur and his colleagues was that species diversities on continents should approach steady states. Furthermore, diversity was thought to be related to rates of evolution (MacArthur 1972; Cody and Diamond 1975). Diversity was used to provide explanations of adaptive radiation, to substantiate the community stability hypothesis, and to describe latitudinal differences in populations. The theory of species diversity and community stability (MacArthur 1972) became a vital force for a number of students of evolutionary ecology and biogeography (Cody and Diamond 1975).

Rates of evolution, migration, and extinction of species obviously affect the diversity of species in forests (Harper 1977). Stebbins (1950, 1974) described how these variables affect the diversity of flowering plants. He did not report evidence that increased diversity of species resulted in increased rates of evolution, migration, and extinction. For example, Stebbins presented no evidence for faster rates of speciation in the highly diverse tropical forests than for the less diverse temperate forests. Rather, evidence suggests that chromosomal variations are more likely to survive in a mosaic of diverse habitats than in an equal area with a uniform habitat (Dobzhansky and others 1977). Similar relationships are described by Mayr (1970) for animals.

The concept of increasing community stability with increasing diversity was strongly criticized by Hairston and others (1968). Loucks (1970) noted that long-term stability reduces diversity. In a recent symposium (Various authors 1970) there was no general agreement on the meaning of stability or on the relationship between stability and diversity. Hill (1973) concluded that diversity, as measured by the Shannon function (Shannon and Weaver 1949), was simply a continuum of index values relating number of species to abundance of individuals. Hill (1973) suggested there was no particular biological merit in using the index; it is another way to illustrate differences in numbers of species and the relative distribution of species for a community.

One difficulty in relating increased diversity of species with increased stability of communities is the lack of any general agreement on how to recognize and quantitatively determine when a community is stable. For a number of subjective definitions of community stability, see MacArthur (1972), Stebbins (1974), Odum (1971), Cody and Diamond (1975), and van Dobben and Lowe-McConnell (1975). Alternatively, Kowal (1971) discusses the significance of stability as an indicator of the behavior of models for ecosystems and as a variable in the biological structure of real communities. Most models are expected to exhibit system stability, not "blow up" in time. Some ecologists expect real communities to exhibit also system stability, to achieve, retain, and return to some preconceived state after a perturbation. Kowal (1971) considers both forms of stability to depend on definitions.

In a recent paper, Odum (1975) defined optimum diversity as a function of the quality and quantity of energy flowing through a system. He says too much, as well as too little, diversity may be destabilizing. Odum does not tell how one can know when diversity is optimum. He urges caution in the use of diversity as a property of stable natural systems, and accordingly, as a desirable feature for the systems of man.

Orians (1975), reviewed more than 50 papers dealing with diversity, stability, and maturity in natural ecosystems. His conclusion is that researchers are unlikely to find general relationships that support the assumptions: succession generates diversity of species and diversity of species enhances the stability of community.

May (1976, page 158) discusses the assumption that increased complexity, which usually means more species, more interactions, and more differences in the elements of a community, increases stability. With the use of mathematical techniques, May (1976) concludes that large, unprecedented perturbations by man may be more traumatic for complex systems than for simple ones. He suggests that this inverts the naive view that "complexity begets stability." May suggests that there is no advantage in attempting to preserve, or even create, complex systems as buffers against man's importunities (May 1976, page 162).

Whittaker (1975) questioned a simple diversity-stability relationship. He suggests that we need to understand the structural-functional design of communities, rather than be preoccupied with diversity.

An alternative to the concept that diversity begets stability is to view plant and animal communities as nonequilibrium systems which do not exhibit thermodynamic forms of stability, but do exhibit organization by virtue of fluctuations in mortality of individuals (Boyce 1977, 1978; Connell 1978). Diversity of species, or any other variable of interest, is then viewed as a consequence of the dynamics of the individuals composing the community. It is unimportant, therefore, whether or not a community is stable, or whether differences in the number and distribution of species are related to a certain definition of stability. An unmanaged forest behaves as a nonequilibrium, aimless community that is the consequence of the behavior of individualistic systems (Boyce 1977, 1978).

An unmanaged forest has no centralized information network and a decision mechanism to direct the mortality and the behavior of individuals. Thus, there can be no goals such as achieving and maintaining a state of stability. If there were such a goal, evolution and extinction could not have occurred as indicated by the fossil and genetic evidence for billions of years (Simpson 1969; Dobzhansky and others 1977). Without a centralized information network, diversity of species is a consequence of the behavior of individualistic systems. Thus, we view unmanaged forests as aimless systems. People can develop information networks and easily become the centralized decision mechanism that converts these aimless communities to directed systems (Boyce, In press).

Algorithms, similar to the ones we described for deer habitat in section 2.2, can be developed to relate the elements of forest diversity to multiple-use objectives. Such algorithms can be developed for any benefit, desirable or undesirable, for any specific forest area. Different forest areas will require adjustments in the algorithms to reflect differences in climates, soils, and topography. In this way, decisions can be made to provide for the diversity of plant and animal communities to meet overall multiple-use objectives. These relationships are discussed in greater detail in section 5.

Confounding in the Shannon-Type of Diversity Indices

In this section we relate the Shannon function to a large number of similar mathematical functions. Procedures for calculation are described. We illustrate how these functions confound classes and proportions of things and, thus, cannot be used to develop relationships for use in management decisions. The Shannon function (Shannon and Weaver 1949) is frequently used to compute dimensionless numbers that express diversity (Pielou 1977; Hair, In press). Because of the widespread use of the Shannon and similar functions, it is important to explain computation methods and the characteristics of these dimensionless numbers.

R. A. Fisher developed a function to describe the expected frequencies with which different species occur in random collection (Fisher, Corbet, and Williams 1943). Weiner (1948) and Shannon (Shannon and Weaver 1949) developed similar functions for measuring uncertainty in communication systems. Brillouin (1962, 1964) used a large number of modifications of the same basic function. Engen (1977) showed how many of these functions, including the Simpson index (Pielou 1977), could be derived from or related to the Shannon function. Tribus (1961) showed that the Shannon function is related to a measure of entropy and can be used in thermodynamics. However, as Hill (1973) pointed out, there is no particular biological significance in the origin of the Shannon and related functions. We describe the Shannon function, since it is frequently used and it is representative of the others.

Indices computed with the Shannon and related functions are dimensionless numbers that confound a number of classes of things and the proportion of things in each class. This confounding is desirable in thermodynamics (Tribus 1961) and in measuring uncertainty in communications. Pielou (1977, page 292) emphasizes the need to be aware of confounding when the Shannon function is used as an index for diversity. Because of confounding, the index cannot be used as an independent variable for some benefit such as the livelihood for deer (figs. 1, 2, and 3).

The Shannon function can be computed any time a group of items can be placed in discrete classes and the proportions of items among classes can be measured. Examples of classes of things and proportions are the number of species and the proportion of individuals assigned to each species, forest types and the proportion of area assigned to each type, species of breeding birds and the proportion of birds in each species, tree species and the proportion of basal area by species, tree species and the proportion of individuals assigned to each species, and species of game animals and the proportion of animals in each species. Classes of things can be considered singly and in many possible combinations. Here we limit ourselves to no more than two classes of things occurring jointly.

Computation of the index is relatively simple. To illustrate the procedure, we use data from inventories of forests in the Mountain Region of North Carolina and of the Pisgah and Nantahala National Forests (Cost 1975). The National Forests are included in the Mountain Region, which consists of 21 western counties in North Carolina.

From the data (Cost 1975) we prepare a table of forest types and the proportion of area in each type for each of the forest areas (table 1). Computation begins by multiplying each proportion (p) by the natural logarithm of that value. For example, on the Pisgah National Forest the oak-hickory type occupies 74.5 percent of the area. The number, 0.745, is multiplied by the natural logarithm of 0.745, which is -0.2944. The product is -0.219. Since the logarithms of numbers less than 1 are negative, the product is multiplied by -1 to produce a positive value (table 1). Then, for each forest area the logarithmic proportions (plnp) are summed to produce the diversity index. The letter H' is used to symbolize diversity index because this is the symbol used in most of the biological literature. Natural logarithms are used because of convention.

The Shannon function is usually written in the form:

$$H' = -K\sum_{i=1}^{n} pi \ln pi$$

Where K is a constant, usually -1, that amounts to converting H' to a positive value. Pi is the proportion of the ith class.

Table 1.--Computation of the Shannon diversity index for areas of forest types found on the Pisgah and the Nantahala National Forests and the Mountain Region Survey in North Carolina

Forest types	Forest areas					
	Pisgah National Forest		Nantahala National Forest		Mountain Region Survey	
	Percent	p·lnp[1]	Percent	p·lnp[1]	Percent	p·lnp[1]
White pine-hemlock	2.4	0.090	--	--	3.4	0.115
Spruce-fir	1.2	.053	--	--	.3	.017
Loblolly pine	--	--	1.7	0.069	.4	.022
Shortleaf pine	--	--	--	--	.6	.031
Virginia pine	1.5	.063	--	--	5.3	.156
Pitch pine	7.1	.188	1.2	.053	1.4	.060
Oak-pine	4.8	.146	7.7	.198	8.7	.212
Oak-hickory	74.5	.219	63.4	.289	69.5	.253
Chestnut oak	5.7	.163	18.5	.312	4.5	.140
Elm-ash-cottonwood	--	--	--	--	0.2	.012
Maple-beech-birch	2.8	.100	7.5	.194	5.7	.163
Total	100.0		100.0		100.0	
H' = Total p·lnp		1.022		1.115		1.181

[1] The proportion of a type (p) multiplied by the natural logarithm of the same value (lnp).

The diversity indices (1.022, 1.115, 1.181) for the three forest areas are dimensionless values (table 1). The size of the values is determined by the number of forest types found on each forest area and by the proportion of land distributed among the forest types. These two quantities are confounded to form a single number. We illustrate this with a few computations.

The maximum possible value of the Shannon diversity index occurs when all forest types are evenly distributed. For example, if the land area of each forest was evenly distributed among the 11 types, the proportion of each type would be 1/11=0.09091. The natural logarithm for 0.09091 is -2.3979, which is multiplied by 0.09091 and -1 to produce the positive value of 0.21799 for each type. This value is multiplied by 11, the number of types to produce the maximum value for H', which is 2.3979. By examining a table of natural logarithms, one can confirm that this value (2.3979) is the natural logarithm of 11. Thus, the maximum possible value for the Shannon index is the natural logarithm of the number of classes of the items.

The degree of evenness of the forest types can be assessed by dividing the diversity index (H') by the maximum possible value, which is the natural logarithm of the number of types. For the Region, the evenness is 1.181/2.3979=0.49; for the Pisgah the evenness value is 1.022/2.3979=0.43; and for the Nantahala the evenness value is 1.115/2.3979=0.46. Since maximum evenness occurs when the value is 1.0, the forest types recorded on the Nantahala are quantitatively illustrated to be less evenly distributed than in the Region but more evenly distributed than on the Pisgah. The greater evenness of types for the Nantahala accounts for the larger diversity index than for the Pisgah, although the Pisgah has more kinds of forest types (table 1). The Shannon diversity indices are shown to confound the number of forest types (classes) and the proportions of area in each forest type (proportion of things in each class) to form the dimensionless numbers, H'.

The important point is that the Shannon-type indices give us very limited information about the diversity of types and other elements of communities. And the Shannon-type indices, because of confounding, cannot be used as independent variables to develop relationships for use in management decisions. We can, however, take advantage of the confounding effect of the functions to indicate how much specified elements of communities are constrained from evenness. This provides the basis for monitoring how the constraint of habitats may affect the livelihood of organisms. The method is described in the next section.

2.5 How to Monitor Constraint in the Distribution of Habitats

In this section we describe and illustrate how a modification of the Shannon-type function can be used to monitor how habitats may be constrained from an even distribution by alternative management plans. The significance of constraint in the distribution of habitats is that the livelihood may be limited for a number of endemic species. Constraint of habitats may be increased or decreased by management actions or by forces unaffected by man.

From section 2.4 evenness is H' divided by the logarithm of the number of habitats being considered. If we subtract the value for evenness from 1, we have a relative measure of constraint, which we call constraint quantum (CQ).

The equation can be expressed in the following form:

$$CQ = \frac{\left(\sum_{i=1} pi \cdot lnpi \right) + lnN}{lnN}$$

Where pi is the proportion of the ith class of habitat, lnpi is the natural logarithm of the proportion of the ith class and lnN is the natural logarithm of the number of classes of habitats.

Shannon recognized this expression as a measure of constraint in languages, which he called redundancy. Ashby (1956) used the word "constraint," and described various uses for the expression. Our concern is to use CQ to monitor when the livelihood for some kinds of endemic organisms is being reduced.

For an illustration we use an inventory of seven kinds of habitats. Each habitat is defined by a stand condition class in a hardwood forest, 6,396 acres, in Buncombe County, North Carolina. Other classifications could be used; however, it is important that the classes meet the operational criteria for elements of diversity (sec. 2.1).

Seedling habitats.--Stands with half of the dominant and codominant trees less than 1 inch d.b.h. (2.5 cm). A few scattered large trees are admitted.

Sapling habitats.--Stands with half of the dominant and codominant trees between 1 and 5 inches d.b.h. (2.5 to 12.4 cm). A few scattered large trees are admitted.

Pole habitats.--Stands with half of the dominant and codominant trees between 6 and 11 inches d.b.h. (12.5 to 27.7 cm). Pole habitats are classified by 2-inch (5 cm) diameter classes as pole-6, pole-8, and pole-10 habitats.

Mature timber habitats.--Stands with half of the dominant and codominant trees between 11 and 16 inches d.b.h. (27.8 to 40.6 cm).

Old-growth habitats.--Stands with half of the dominant and codominant trees larger than 16 inches d.b.h. (40.7 cm).

First we consider a mode of management when no timber is harvested and the forest changes with forces unaffected by man (fig. 4). A dynamic, analytic silviculture technique (Boyce 1977) is used to display changes over time. The proportion of old-growth habitat increases to about 63 percent of the area. The CQ value (*) remains below about 0.2 until year 30, then the constraint quanta increase to about 0.34 by year 110. The increase in constraint results from an increase in the proportion of area in old-growth (O) and in the reduction of area in seedling (S), sapling (A), and pole-6 (6), pole-8 (8), and pole-10 (1) stands. The proportions of areas in the younger habitats are constrained by the large area in old growth. The increasing constraint in the distribution of habitats is monitored by the increase in constraint quanta.

Our concern is with changes in the proportional distribution of habitats, especially an increase in constraints that would limit the availability of one or more habitats. The significance of this information for wildlife is given by Siderits and Radtke (1977):

> "A wildlife plan or program then becomes the establishment of the desirable mixture of various components that will provide the greatest diversity through time and space on a sustained basis. A management plan geared to provide this diversity would have as its goal not a given number of animals of any one species, but a given acreage of quality environment that would support a variety of species in different densities, dependent upon the inherent capability of the area being managed."

We now consider a mode of management (Boyce 1977) in which rates of timber harvest from the mature and old-growth stands and sizes of openings would increase the random proportions and locations of the seven habitats. The CQ values (fig. 5) decline for about 40 years and then remain at about 0.05. The value 0.05 simply indicates less constraint on the distribution of habitats than when the CO values are larger, such as 0.34 (fig. 4). Relatively smaller CQ values indicate a relatively more even distribution of habitats and the livelihood of a greater number of genotypes (sec. 2.2).

From Coyle's (In press) work with spiders, one would expect more different kinds of spiders to be found in the forest with a CQ value of 0.05 than in one with a CQ value of 0.34. However, we do not have enough information to know what ranges of CQ values for this particular forest and for these seven classes of habitats would provide a livelihood for the largest numbers of endemic species. Relationships such as the algorithms for deer (figs. 1, 2, and 3) must be obtained for each kind of forest and for widely diverse kinds of plants and animals.

One could use a modification of the Shannon-type of functions as a relative measure of the constraint of habitats. None of the functions have any particular biological significance. Such functions are nothing more than a relative measure of constraint of habitats from evenness. What is important is that one specifies the number and kinds of habitats and have evidence that diversity of the kinds of habitats described relate to the potential livelihood of most, if not all, endemic species. The significance of the constraint quantum lies in its use to indicate when one or more of these important kinds of habitats is being constrained beyond an undesirable distribution.

YEARS

```
            PERCENT OF AREA BY HABITATS AND THE CONSTRAINT QUANTA VALUES

    .0             .1             .2             .3             .4 S
    .0             .2             .4             .6             .8 A681MO*
  .0- O MS- -8-*   A  - -16 - - - - - - - - - - - - - - - - - - -
    . O SM    8     A     6        .              .              . 61,8*
    . OS  M  8     A    6         .              .              . 61,8*
    .  S   M * 8  A.    61        .              .              . SO
    . SO    M* 8  A.  6 1         .              .              .
    . SO    M*  8 A.  6 1         .              .              .
    .S O    *M  8 A. 6 1          .              .              .
    .S O    * M 8A .6  1          .              .              .
    .S  O   *  M A .6  1          .              .              . A8
    .S  O   *  M A 6   1          .              .              . A8
 10.-S- O - * - A86 - -1- - - - - - - - - - - - - - - - - - - - - AM
    S     C*   A68M.   1          .              .              .
    S      O  A6 8 .M 1           .              .              . O*
    S      * A  8  .  1           .              .              . A6O,1M
    S       A  8   .  1M          .              .              . A6*,8O
    .S     A* 8  O . 1   M        .              .              . A6
    .S    A *8     O1    M        .              .              . A6
    .S   6A  8*    .1O    M       .              .              .
    .S   A  8  *   1   O   M      .              .              . A6
    .S  6A 8    * 1.     O M      .              .              .
 50.-S- 6A8 - - -1- - - - -MO - - - - - - - - - - - - - - - - - - 1*
    .S  6A8     1 *.       M  O   .              .              .
    .S 6 A     1   *       M    O .              .              . A8
    .S 6 A    1    .*     M       O              .              . A8
    . S68A    1    . *    M       .O             .              .
    . S68A   1     .  *  M        .  O           .              .
    . S68A  1      .   * M        .    O         .              .
    . S6 A  1      .    M         .     O        .              . 68,M*
    . S6 A 1       .   M *        .       O      .              . 68
    . S6 A1        .  M   *       .        O     .              . 68
 90.- S6-A1 - - - - - M - * - - - - - - - - O - - - - - - - - - - 68
    . S6 A1        . M     *      .          O   .              . 68
    . S6 1A        .M      *     .           O  .              . 68
    . S6 1A        M       *     .            O .              . 68
    . S6 1A       M.       *     .             O.              . 68
    . S6 1A       M.        *    .             O.              . 68
    . S61 A      M .        *    .              O              . 68
    . S61 A      M .        *    .              .O             . 68
    .  S1  A    M  .        *    .              .O             . S68
    .  S1  A   M   .         *   .              .O             . S68
130.- -S1 -A- -M- - - - - - - * - - - - - - - - - O - - - - - - - S68
    .  S1  A   M   .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A  M    .          *   .              . O            . S68
    .  S1  A M     .          *   .              . O            . S68
    .  S1  A M     .          *   .              . O            . S68
    .  S6  A M     .         *    .              . O            . S8,61
    .  S6  A M     .         *    .              . O            . S8,61
    .  S6  A M     .         *    .              . O            . S8,61
170.- -S6 - A - - - - - - - -*- - - - - - - - - - -O- - - - - - - S8,61,AM
```

Figure 4.--When no timber is harvested, the proportion of old-growth habitat (O) increases and constrains the amount of mature timber (M), pole timber (1, 8, 6), saplings (A), and seedlings (S). This constraint is indicated by the rise in constraint quanta (*).

PERCENT OF AREA BY HABITATS AND THE CONSTRAINT QUANTA VALUES

YEARS

```
    .0             .1             .2             .3             .4 S
    .0             .2             .4             .6             .8 A681MO*
  .0- O MS- -8-*- -A- - -16 - - - - - - - - - - - - - - - - - - -
    . O SM    8    A     6        .              .              . 61,8*
    . OS  M   8    A    6         .              .              . 61,8*
    . OS   M * 8  A.   61         .              .              .
    . OS    M* 8  A.  6 1         .              .              .
    . OS    M*  8 A.  6 1         .              .              .
    . OS    *M  8 A. 6 1          .              .              .
    . O S   *M  8 A.6  1          .              .              .
    . O S  *  M  8A.6  1          .              .              .
    . O S  *  M  8A6   1          .              .              .
 10.- O S -*- -M-8A - -1- - - - - - - - - - - - - - - - - - - - - A6
    .  O S*     M6A.   1          .              .              . 68
    .  O S*    6 8A.  1           .              .              . 8M
    .   OS    6 8 A.  1           .              .              . AM,S*
    .   OS   6  8 AM  1           .              .              . S*
    .    S   6 8  A.M1            .              .              . SO*
    .    SO  6 8   AM1            .              .              . S*
    .   * SO6 8    A1             .              .              . 1M
    .   * SO6 8    A1M            .              .              .
    .   * S 68     A M            .              .              . A1,6O
 50.- - * S 68- - -1AM- - - - - - - - - - - - - - - - - - - - - - 8O
    .   * S 68    1.A             .              .              . AM,8O
    .   * S 680   1.A             .              .              . AM
    .   * S 6 O  1 .MA            .              .              . 68
    .  *  S 6 O  1 .MA            .              .              . 68
    .  *  S 6  O 1 M A            .              .              . 68
    .  *  S 6  O1  M A            .              .              . 68
    .  *  S 6  O1 M.  A           .              .              . 68
    .  *  S 86 O1 M.  A           .              .              .
    .  *  S 86 O1 M.  A           .              .              .
 90.- -*- -S86- 1M- - A - - - - - - - - - - - - - - - - - - - - - 1O
    .  *   S 6  1M .  A           .              .              . 68,1O
    .  *   S 6  1M .   A          .              .              . 68,1O
    .  *   S 6  1  .   A          .              .              . 68,1MO
    .  *   S 6  1  .   A          .              .              . 68,1MO
    .  *   S 6 O1  .   A          .              .              . 68,1M
    .  *   S 6 O1  .   A          .              .              . 68,1M
    .  *  S  6 O1  .   A          .              .              . 68,1M
    .  *  S  6 O1  .   A          .              .              . 68,1M
    .  *  S  6 M1  .   A          .              .              . 68,MO
130.- -*- S -6-M1 - - -A- - - - - - - - - - - - - - - - - - - - - 68,MO
    .  *  S  6 M1  .   A          .              .              . 68,MO
    .  *  S  86M1  .   A          .              .              . MO
    .  *  S  86M1  .   A          .              .              . 6O
    .  *  S  86M1  .   A          .              .              . 6O
    .  *  S  86M1  .   A          .              .              . 6O
    .  *  S  86M1  .   A          .              .              . 6O
    .  *  S   6M1  .   A          .              .              . 68O
    .  *  S   6M1  .   A          .              .              . 68O
    .  *  S   6M 1 .   A          .              .              . 68O
170.- -*- S -O6 M1- - -A- - - - - - - - - - - - - - - - - - - - - 68
```

Figure 5.--The constraint quanta of about 0.05 for habitats in this particular forest results in a certain combination of benefits being available at a relatively high rate. S = seedling habitat; A = sapling habitat; 6 = pole-6 habitat; 8 = pole-8 habitat; 1 = pole-10 habitat; M = mature timber habitat; 0 = old-growth habitat.

3. HOW TO COMPARE THE DIVERSITY OF TREE SPECIES

3.1 Direct Comparisons

Lists of species by some meaningful characteristic provide the simplest way to compare diversity of tree species in the National Forests and in the Region (Oosting 1956; Harper 1977; May 1976). One of the most meaningful methods is to use a matrix for the proportions of species by size classes. This method provides a list of the most obvious species, information about the distribution of species by size classes, and data that may be used in logarithmic, bionomic, and geometric transformations (Pielou 1977). We illustrate this method.

From the inventory data for the Mountain Region Survey in North Carolina (Cost 1975), we prepare three matrices of the proportions of trees in 32 species and species groups and in 12 diameter classes (tables 2, 3, and 4). Each number in the matrix is the percent of total individuals recorded and represents a unit of diversity of species and size classes. The nomenclature of the classes of species is listed in the Forest Survey Handbook (U.S. Dep. Agric., Forest Service 1967). Individuals are recorded regardless of their position in the stand and regardless of the condition class of the stand. Species are grouped into classes, either because of the difficulty of identifying individuals in all stages of development, or because the individuals represent less than 0.01 percent of the total.

Two-inch diameter classes are used to classify all stems from 1 to 20.9 inches d.b.h. (tables 2, 3, and 4). Because of the low frequency of trees larger than 20 inches, one class includes trees from 21.0 to 28.9 inches and a last class includes all trees larger than 29 inches d.b.h. The diversity of diameter classes is illustrated with logarithmic paper (fig. 6). These kinds of curves have been known for many years (Husch and others 1972). Certain kinds of management actions, especially those that limit the presence of stands in certain diameter classes, can change the elevation, shape, and slope of these curves (Assmann 1970; Smith 1962). For example, the higher elevation of the curve for the Pisgah National Forest indicates a larger average diameter for trees in the Pisgah than in the Nantahala and in the Region.

The logarithmic relationships can be used to examine the relative diversity of species by diameter classes. Stands, whether of mixed species or of a single species, are organized over time by the mortality of individualistic systems (Boyce 1977, In press). Different genotypes form with the environment different individualistic systems, each having a different probability that the essential variables, such as water content, and respiration rates, can be maintained within the limits of life. Thus, we would expect, and we find, different natural rates of mortality among genotypes and thus, species. The significance of these natural, biological mechanisms is to change the diversity of species as groups of stands change to larger diameter classes.

For example, we find a greater diversity of tree species in the smaller diameter classes, typical of seedling and sapling habitats, than in the larger diameter classes, typical of mature and old-growth habitats (for definitions of the classes of habitats, see section 2.5). We illustrate this relationship with a limited number of examples.

Table 2.--Relative numbers of tree species for diameter classes for the Mountain Region Survey in North Carolina

Tree species	Diameter class												
	1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-28.9	29.0 and larger	Total
	Percent												
Shortleaf pine	0.40	0.21	0.14	0.18	0.14	0.07	0.04	(1/)	(1/)	(1/)	(1/)	--	1.18
Loblolly pine	.08	.09	.03	.04	.01	--	--	--	--	--	--	--	.25
Virginia pine	2.30	1.05	.82	.48	.25	.08	.03	0.01	(1/)	(1/)	--	--	5.02
Pitch pine	.38	.39	.29	.22	.15	.06	.03	.02	0.01	(1/)	(1/)	--	1.55
Table-Mountain pine	.04	--	.03	.03	(1/)	.01	.01	(1/)	--	--	(1/)	--	.12
Eastern white pine	1.99	.56	.21	.27	.15	.09	.07	.05	.03	0.01	0.02	(1/)	3.45
Eastern hemlock	.80	.28	.21	.07	.05	.02	.03	.02	.01	.01	.01	(1/)	1.51
Spruce and fir	.39	.08	.02	.04	.02	.01	(1/)	(1/)	(1/)	--	--	--	.56
Cedars	.07	.10	.02	(1/)	(1/)	--	--	--	--	--	--	--	.19
Select white oaks	2.19	1.03	.43	.24	.15	.11	.06	.03	.04	.02	.02	(1/)	4.32
Select red oaks	.85	.68	.31	.20	.14	.12	.08	.06	.04	.03	.04	0.01	2.56
Chestnut oak	1.88	1.18	.68	.46	.32	.20	.15	.10	.05	.04	.05	.01	5.12
Other white oak	.22	.03	.04	.01	.02	.01	(1/)	(1/)	--	--	--	(1/)	.33
Other red oak	1.86	1.24	.78	.50	.36	.22	.15	.09	.05	.03	.03	(1/)	5.31
Hickory	2.56	.87	.37	.24	.17	.11	.07	.04	.03	.01	.01	(1/)	4.48
Yellow birch	.19	.23	.16	.02	.02	(1/)	.01	.01	(1/)	(1/)	(1/)	(1/)	.64
Hard maple	.71	.26	.14	.05	.02	.02	.02	.01	.01	(1/)	(1/)	(1/)	1.24
Soft maple	8.07	2.37	.93	.37	.21	.12	.07	.04	.02	.01	.01	(1/)	12.22
Beech	1.54	.32	.19	.07	.05	.04	.03	.01	.01	(1/)	.01	--	2.27
Sweetgum	--	.03	.01	.01	(1/)	(1/)	--	(1/)	--	--	--	--	.05
Tupelo and blackgum	3.36	.47	.16	.07	.04	.04	.02	.01	.01	(1/)	(1/)	--	4.18
Ash	.25	.07	.09	.07	.02	.03	.02	.01	.01	(1/)	(1/)	(1/)	.57
Cottonwood	--	--	--	--	--	--	--	--	--	--	(1/)	--	(1/)
Basswood	.31	.14	.05	.05	.03	.03	.01	.01	(1/)	(1/)	(1/)	(1/)	.63
Yellow-poplar	3.04	1.41	.70	.52	.36	.26	.16	.08	.04	.02	.02	(1/)	6.61
Bay and magnolia	.29	.16	.03	.04	.02	.01	.01	.01	(1/)	(1/)	(1/)	(1/)	.57
Black cherry	.45	.05	.07	.03	.02	.01	.01	(1/)	(1/)	(1/)	(1/)	--	.64
Black walnut	.07	.05	.02	.03	.01	.01	(1/)	(1/)	(1/)	(1/)	(1/)	--	.19
Sycamore	--	--	--	--	.01	--	--	--	--	--	--	--	.01
Black locust	.81	.38	.33	.30	.18	.11	.05	.02	.01	(1/)	.01	--	2.20
Elm	.05	--	--	--	--	--	--	--	(1/)	--	--	--	.05
Other eastern hardwoods	22.36	6.46	1.93	.70	.28	.12	.06	.03	.02	.01	.01	(1/)	31.98
Total	57.51	20.19	9.19	5.31	3.20	1.91	1.19	.66	.39	.19	.24	.02	100.00

1/ Less than 0.01 percent.

Table 3.--Relative numbers of tree species for diameter classes for the Pisgah National Forest

Tree species	Diameter class												
	1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-28.9	29.0 and larger	Total
	Percent												
Shortleaf pine	--	--	0.15	0.17	0.16	0.07	0.04	--	--	--	--	--	0.59
Loblolly pine	--	--	--	--	--	--	--	--	--	--	--	--	--
Virginia pine	0.32	0.32	.20	.24	.08	.04	.02	--	--	--	--	--	1.22
Pitch pine	.30	2.43	.90	1.15	.44	.20	.03	0.05	0.02	0.01	--	--	5.53
Table-Mountain pine	--	--	.10	.24	--	.09	.04	.02	--	--	--	--	.49
Eastern white pine	.33	.32	.33	.51	.22	.14	.01	.07	.03	.01	0.04	0.01	2.02
Eastern hemlock	1.23	--	.94	.20	.04	.08	.10	.05	--	.07	.03	.02	2.76
Spruce and fir	--	--	--	.15	--	--	--	--	--	--	--	--	.15
Cedars	--	--	--	--	--	--	--	--	--	--	--	--	--
Select white oaks	.32	.28	.75	--	.03	.05	--	.05	.05	.05	.05	(1/)	1.63
Select red oaks	1.21	1.50	.39	.37	.18	.33	.18	.17	.05	.16	.16	.05	4.75
Chestnut oak	2.10	.30	1.55	.86	.47	.35	.21	.14	.11	.10	.13	.03	6.35
Other white oak	--	--	--	--	--	--	--	--	--	--	--	--	--
Other red oak	.87	--	1.39	.81	.30	.24	.10	.14	.05	.04	.02	.01	3.97
Hickory	4.03	.63	.16	.32	.34	.07	.06	.05	.02	.02	.04	--	5.74
Yellow birch	.28	--	.08	.18	.11	.02	.07	.05	--	.01	.02	--	.82
Hard maple	.28	--	.28	.15	--	.03	--	--	--	(1/)	(1/)	.01	.75
Soft maple	10.87	3.63	1.55	.49	.42	.19	.15	.04	.05	.01	.02	.01	17.43
Beech	.30	.88	.21	--	.13	.03	.04	.03	.04	--	.02	--	1.68
Sweetgum	--	--	--	--	--	--	--	--	--	--	--	--	--
Tupelo and blackgum	4.84	--	.35	.15	--	.08	.02	.03	.02	.01	.01	--	5.51
Ash	--	--	.15	--	--	.03	--	--	--	--	--	--	.18
Cottonwood	--	--	--	--	--	--	--	--	--	--	--	--	--
Basswood	--	--	--	.03	.02	.05	.01	--	--	.01	--	--	.12
Yellow-poplar	.60	1.74	.43	.50	.49	.36	.22	.11	.09	.05	.05	--	4.64
Bay and magnolia	--	--	--	--	--	--	--	--	--	--	--	--	--
Black cherry	.28	--	.05	--	.02	.06	.01	.02	--	(1/)	--	--	.44
Black walnut	--	--	--	--	--	--	--	--	--	--	--	--	--
Sycamore	--	--	--	--	--	--	--	--	--	--	--	--	--
Black locust	.33	.65	.38	.14	.05	.23	.09	.06	--	--	--	--	1.93
Elm	--	--	--	--	--	--	--	--	--	--	--	--	--
Other eastern hardwoods	16.81	9.12	2.74	1.55	.55	.30	.09	.09	.01	.03	.01	--	31.30
Total	45.30	21.80	13.08	8.21	4.05	3.04	1.49	1.17	.54	.58	.60	.14	100.00

1/ Less than 0.01 percent.

Table [illegible].--Relative numbers of tree species for diameter classes for the Nantahala National Forest

Tree species	Diameter class												
	1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-28.9	29.0 and larger	Total
	Percent												
Shortleaf pine	--	--	--	0.11	0.23	0.09	0.07	0.01	--	0.01	--	--	0.52
Loblolly pine	--	0.62	0.30	.38	.05	--	--	--	--	--	--	--	1.35
Virginia pine	--	.21	.06	.12	.05	.01	--	--	--	--	--	--	.45
Pitch pine	1.15	1.38	.19	.33	.10	.04	.04	.03	0.01	--	--	--	3.27
Table-Mountain pine	--	--	.07	--	--	--	.02	--	--	--	0.01	--	.10
Eastern white pine	0.46	.40	.04	.27	.10	.05	.05	.04	--	.01	.04	0.01	1.47
Eastern hemlock	1.32	.46	.28	.13	.06	.01	.06	.03	.01	.02	.02	.02	2.42
Spruce and fir	--	--	--	--	--	--	--	--	--	--	--	--	--
Cedars	--	--	--	--	--	--	--	--	--	--	--	--	--
Select white oaks	2.02	1.55	.51	.31	.16	.11	.04	.02	.10	.02	.06	--	4.90
Select red oaks	1.53	2.42	.73	.30	.32	.18	.08	.05	.04	.03	.09	.02	5.79
Chestnut oak	3.27	3.10	.70	.41	.41	.14	.17	.17	.05	.07	.13	.02	8.64
Other white oak	--	--	--	--	--	.02	--	.01	--	--	--	--	.03
Other red oak	1.45	1.72	.80	.63	.57	.40	.38	.13	.10	.05	.07	.01	6.31
Hickory	5.38	2.83	.83	.37	.20	.22	.17	.06	.06	.01	.02	(1/)	10.15
Yellow birch	.63	--	.12	--	.03	--	.02	.01	.01	.01	.01	.01	.85
Hard maple	.20	--	--	--	--	--	--	.01	--	--	.01	--	.22
Soft maple	10.38	3.99	1.23	.54	.21	.13	.04	.06	.02	--	.02	--	16.62
Beech	2.78	.20	.20	.05	--	.04	.11	.02	.01	.01	.01	--	3.43
Sweetgum	--	--	--	--	--	--	--	--	--	--	--	--	--
Tupelo and blackgum	2.42	.40	--	.10	--	.03	--	--	--	--	--	--	2.95
Ash	--	--	.21	.05	--	.04	.02	--	.02	--	--	--	.34
Cottonwood	--	--	--	--	--	--	--	--	--	--	--	--	--
Basswood	.23	.69	--	--	--	.07	.03	.03	--	--	.01	--	1.06
Yellow-poplar	1.38	.43	.28	.35	.18	.10	.07	.04	--	.02	.02	(1/)	2.87
Bay and magnolia	--	--	--	--	--	--	--	--	--	--	--	--	--
Black cherry	.46	--	--	--	.03	--	.03	--	--	--	--	--	.52
Black walnut	--	--	--	--	--	--	--	--	--	--	--	--	--
Sycamore	--	--	--	--	--	--	--	--	--	--	--	--	--
Black locust	.46	.44	--	.05	.13	.04	--	.01	.04	--	--	--	1.17
Elm	--	--	--	--	--	--	--	--	--	--	--	--	--
Other eastern hardwoods	13.77	7.31	2.01	.82	.33	.13	.11	.03	.03	.01	.02	(1/)	24.57
Total	49.29	28.15	8.56	5.32	3.16	1.85	1.51	.76	.50	.27	.54	.09	100.00

1/ Less than 0.01 percent.

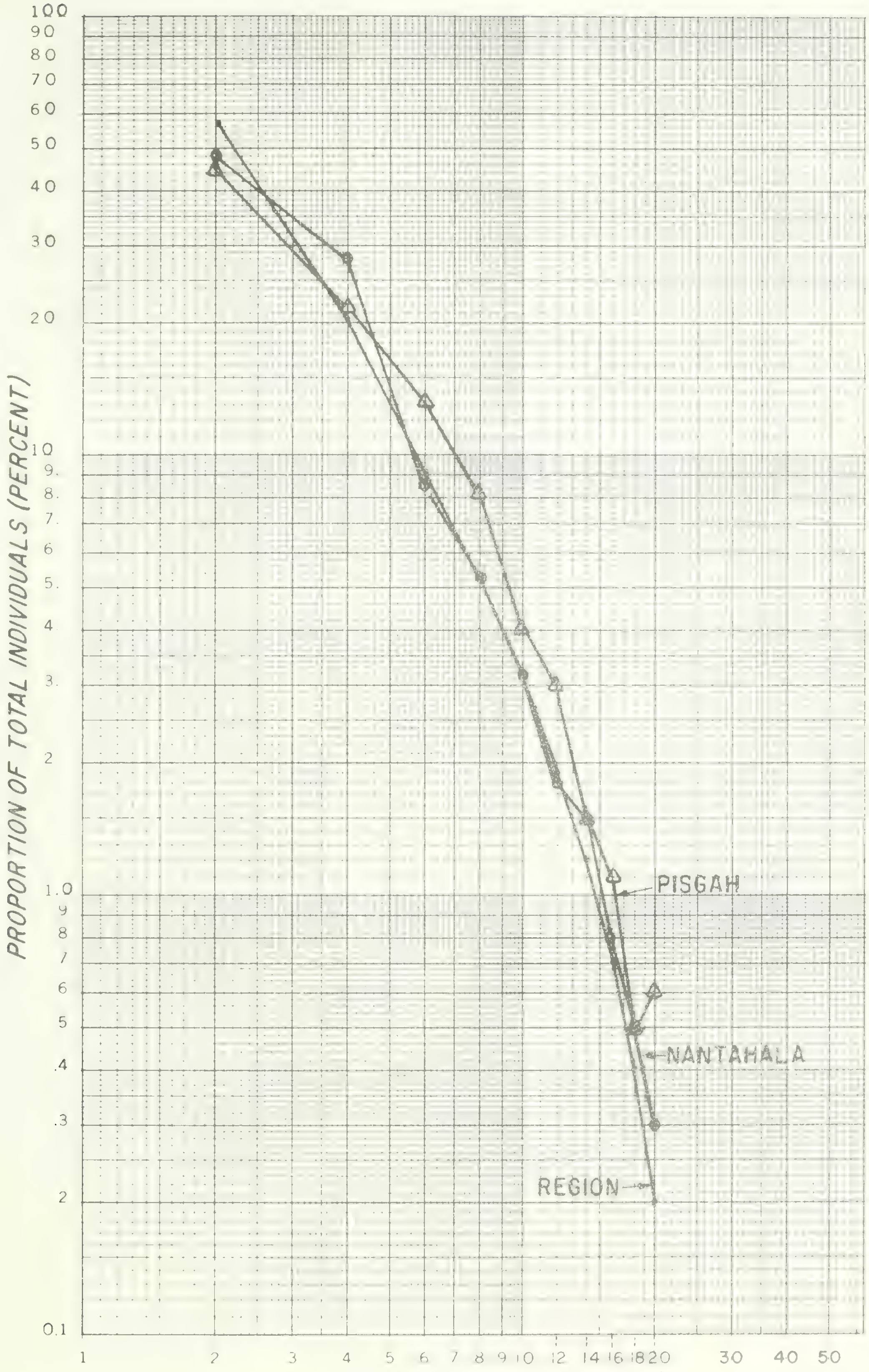

Figure 6.--The distribution of diameter classes for all species in the Mountain Region Survey and in the Pisgah and Nantahala National Forests.

The relatively infrequent species, labeled "other eastern hardwoods," such as dogwood and sourwood, represents 25 to 32 percent of the total individuals and 28 to 29 percent of the stems less than 5 inches d.b.h. (tables 2, 3, and 4). This kind of distribution is the common case for biological communities (Fisher, Corbet, and Williams 1943; Pielou 1977). Distributions are not random but are often logarithmic or follow some geometric form. Some of these species achieve large sizes, but most of them rarely become dominant and codominant trees. We can compute the proportions of these and other species by diameter classes by dividing each percentage figure by the total for the diameter class. For example, in the 2-inch-diameter class for the Region, the other eastern hardwoods represent 22.36/57.51=38.8 percent of the stems recorded.

We plot the percentages by diameter classes on logarithmic graph paper (fig. 7). The proportions of these infrequent hardwoods rapidly decline as the diameters increase above 4 inches. This is a consequence of relatively high rates of mortality as these species increase in diameter. From the graph (fig. 7), one can observe no outstanding differences between the Region and the National Forests.

Next to the infrequent hardwood species, soft maple has the highest percentage of any of the other species or species groups recorded (tables 2, 3, and 4). Soft maple represents 12 to 17 percent of all the numbers of stems recorded. However, 8 to 11 percent of these soft maple stems are less than 3 inches in diameter. Soft maple represents one of a number of species that has very high rates of mortality in the smaller diameter classes. This can be observed by plotting the proportions of soft maple by diameter classes on logarithmic graph paper (fig. 8). The rates of mortality for soft maple are not outstandingly different between the National Forests and the Region. The proportion of soft maple rapidly declines as diameter increases.

As a genus, the oaks represent a slightly larger proportion of total stems (17 to 26 percent) than soft maple. In contrast to soft maple, the oaks represent a group of species in which rates of mortality are relatively low, and consequently the proportion of oaks increases with increasing diameter class (fig. 9). The oak genus makes up more than half of all the trees larger than 16 inches in diameter. And the oaks are the most common dominant and codominant trees on both the Region and on the National Forests.

Large numbers of other hardwood and coniferous species have different rates of mortality with increasing diameter classes. These differential rates of mortality result in different combinations of species occupying dominant and codominant positions as stands age from seedling to old-growth habitats. Because of these changes, the distribution of species in seedling habitats is not directly related to the distribution of dominant and codominant species in mature and old-growth habitats. Some of these kinds of changes which result from different rates of mortality of species over time can be observed in the data reported by Della-Bianca (1971, 1975); Lamson and Smith (1978); Sander, Johnson, and Watt (1976); and Smith and Lamson (1977). Thus, interpretations of the diversity of species should consider differential rates of mortality, and the variety of stand condition classes.

Comparisons should consider, also, characteristics of indigenous soils. For example, pitch pine is more abundant in the National Forests than in the Region (tables 2, 3, and 4). The interpretation is that pitch pine naturally regenerates and survives to maturity on certain kinds of dry ridges. The kinds of ridges are more abundant on the National Forests, especially on the Pisgah, than on the Region. Thus, the differences in pitch pine are interpreted to be due to differences in indigenous soils.

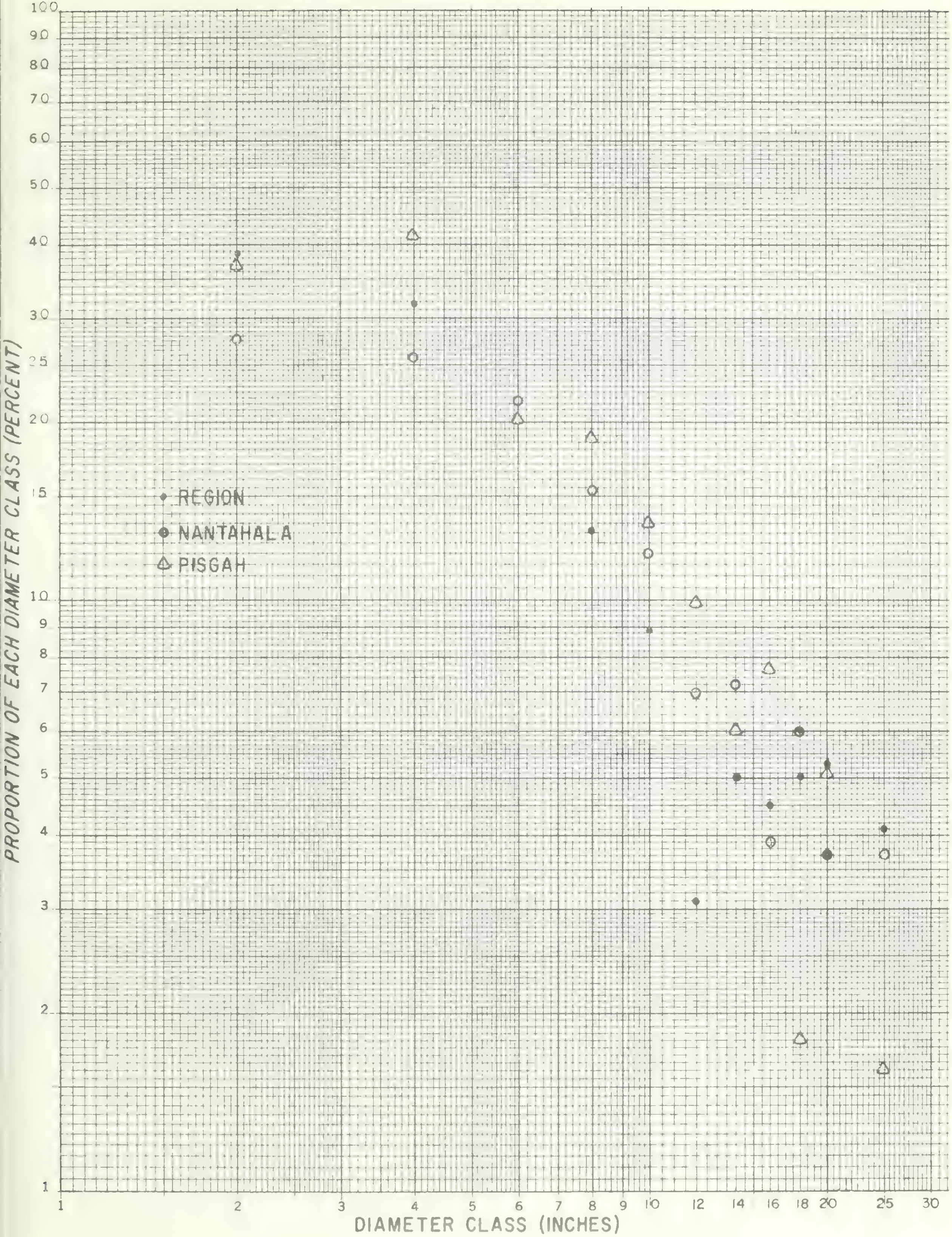

Figure 7.--The proportion of each diameter class represented by "other hardwood speci
(· = Mountain Region Survey; x = Pisgah; and o = Nantahala National Forest).

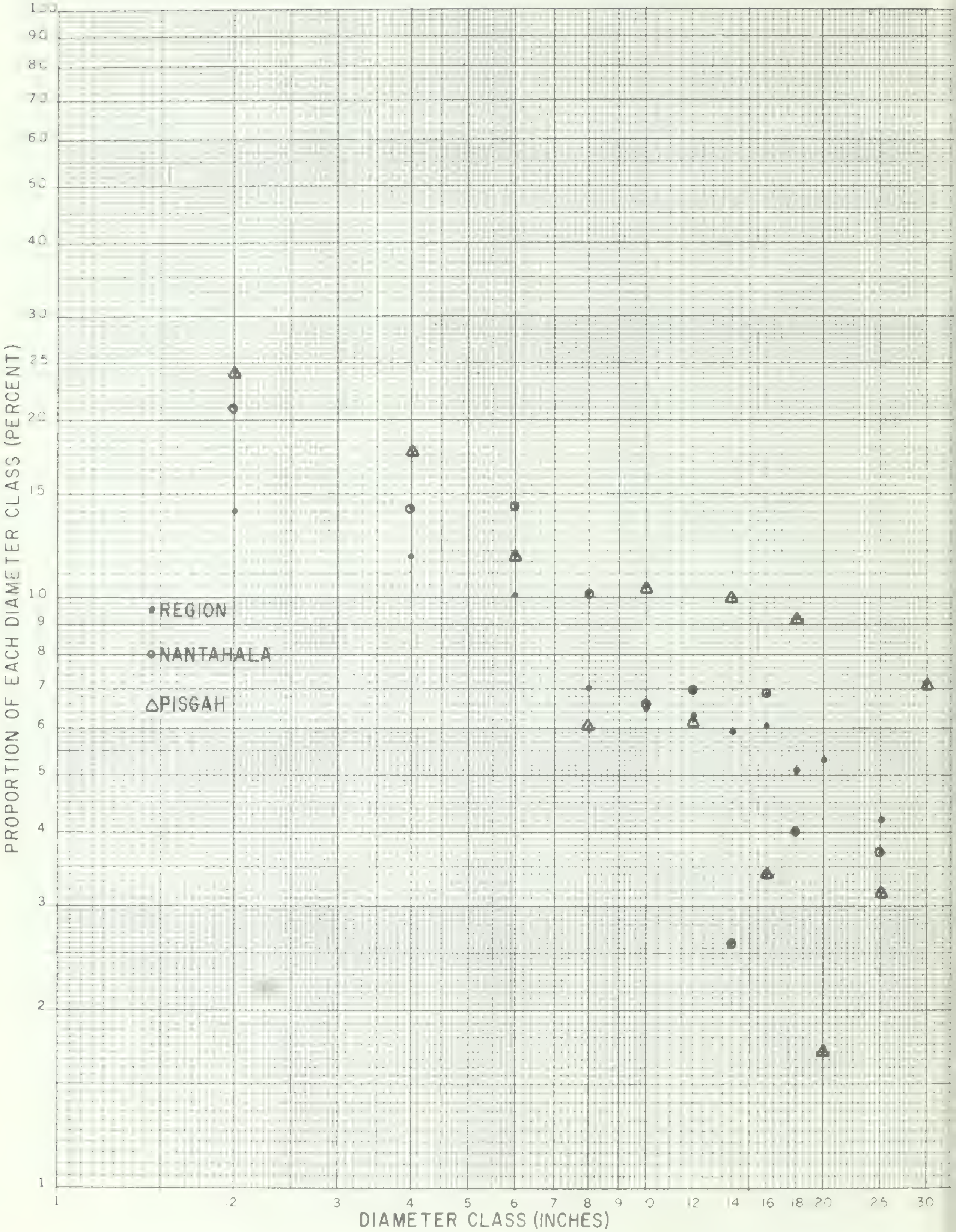

Figure 8.--The proportion of each diameter class represented by soft maple (· = Mountain Region Survey; x = Pisgah; and o = Nantahala National Forest).

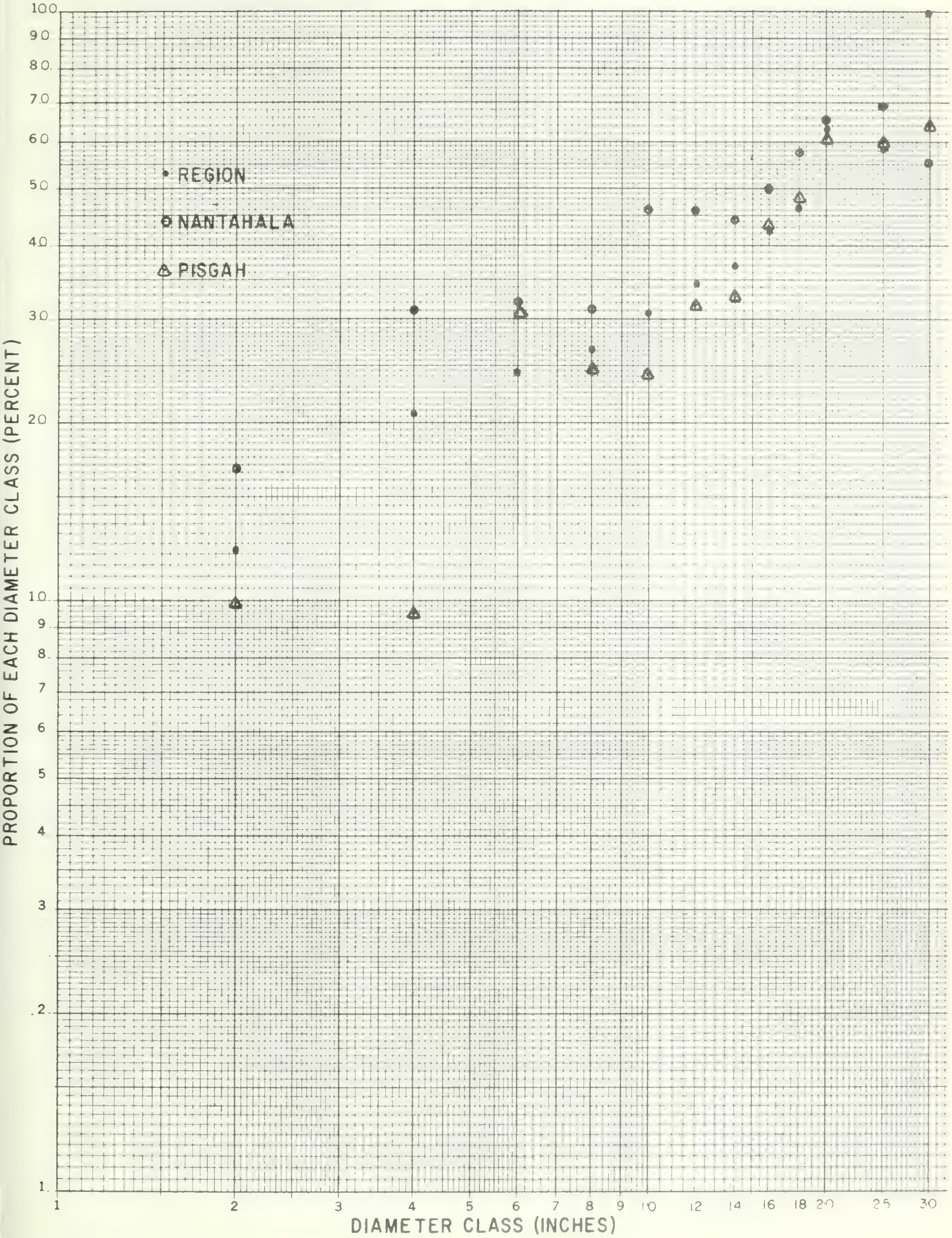

Figure 9.--The proportion of each diameter class represented by oaks (· = Mountain Region Survey; x = Pisgah; and o = Nantahala National Forest).

Our conclusion is that a direct comparison of the proportions of species by diameter classes is an effective way to compare the diversity of tree species in the Region and in the National Forests. It is important to use larger areas of land which provide a representative sample of diameter classes and species. Similarities and differences may be illustrated by logarithmic transformations of the data.

3.2 Indirect Comparisons with the Shannon Function

Because of the widespread use of the Shannon function for species diversity, we illustrate its use and its deficiencies. We find the Shannon function provides inadequate information.

For each of the three matrices (tables 2, 3, and 4), the joint diversity of species and diameter classes, H'(S,DC), the diversity for species, H'(S), and the diversity for diameter classes, H'(DC), were computed by the methods illustrated in section 2.4 (table 1). For example, in the Mountain Region Survey, 8.07 percent of the soft maples is less than 3 inches d.b.h. (table 2). The natural logarithm of this value is multiplied by itself to form the logarithmic proportions. These values are summed to form the joint diversity index. H'(S,DC)=3.8036 (table 2). The totals for rows are used for species (S) and the totals for columns are used for diameter classes (DC). The same computations are made for the two National Forests (tables 3 and 4). Evenness is computed as described in section 2.4. Values for the Shannon index and for evenness are listed for the three forest areas (table 5). The numbers are dimensionless and confounded (sec. 2.4).

Table 5.--The Shannon diversity and evenness indices for tree species, diameter classes, and the joint events for the Mountain Region Survey, the Pisgah and the Nantahala National Forests

Category	Mountain Region Survey	Pisgah National Forest	Nantahala National Forest
	- - - - - -	Dimensionless	- - - - - -
Diversity			
Species	2.54	2.37	2.48
Diameter class	1.34	1.61	1.43
Joint event	3.80	3.74	3.78
Evenness			
Species	.73	.68	.71
Diameter class	.54	.65	.58
Joint event	.64	.63	.63

One can spend considerable time attempting to attach some kind of meaningfulness to the Shannon numbers (table 5). These kinds of numbers provide inadequate information for a rational interpretation of diversity in species and diameter classes, as described in section 3.1. We do not recommend the use of Shannon-type functions for comparing the diversities of tree species.

4. HOW TO COMPARE THE DIVERSITY OF COMMUNITIES AND ANTICIPATE CHANGES

4.1 Diversity of Communities

In this section we use lists of forest types by stand condition classes to illustrate a simple way to compare the diversity of plant and animal communities. A matrix of forest types by stand condition classes is prepared (tables 6, 7, and 8). Data are from Cost (1975). Each cell in the matrix is operationally defined as an element of diversity (sec. 2.1).

The oak-hickory type represents two-thirds to three-fourths of all the stands. And, most of the oak-hickory stands (39 to 50 percent) are in the sawtimber and old-growth condition classes. The chestnut oak type, 18 percent of the Nantahala, is an important type. Maple-beech-birch, pitch pine, and Virginia pine types each represent less than 10 percent of the forests.

Some of the differences (tables 6, 7, and 8) include: 30 kinds of different units of diversity recorded in the Region, 14 in the Pisgah, and 12 in the Nantahala; a greater proportion of sawtimber stands is recorded on both National Forests than in the Region; and the Pisgah has the highest proportion of nonstocked stands. These differences can be related to climate, soil types, and kinds of topography. For example, the nonstocked areas on the Pisgah are relatively steep areas with rocky soils. Nonstocked means the areas do not have a minimum number of commercial species of trees (Cost 1975). These areas do have an abundance of other kinds of plants and do contribute to the diversity of plant and animal communities.

An analysis of the reasons for the differences among the National Forests and the Region could provide important information for ways to maintain the current diversity of types and condition classes. Repeated inventories over time can provide data for future comparisons of forest types by stand condition classes (tables 6, 7, and 8) and for detecting major changes. One could use additional elements of diversity, such as the average area of stands. The elements used, however, should be meaningful, definitive, and measurable (sec. 2.1).

Comparisons such as this are useful primarily for monitoring changes in major elements of diversity over time. A more important consideration is how to anticipate change.

4.2 How to Anticipate Changes in the Diversity of Communities

In this section we use a dynamic analytic silviculture technique (Boyce 1977, 1978) to illustrate a way to anticipate changes in plant and animal communities. We show how one can anticipate changes in the diversity of communities under natural forces unaffected by man and under forces directed by man.

For the illustration we use an inventory of a hardwood forest, 6,396 acres, in Buncombe County, North Carolina. Each of seven stand condition classes is defined as a habitat (sec. 2.5). We use one forest type, oak-hickory. In practice more than one forest type may be used and habitats would then be defined as one of a number of stand condition classes in one of a number of forest types.

Table 6.--Diversity of forest types by condition classes of stands for the Mountain Region Survey in North Carolina

Forest types	Condition classes of stands				
	Sawtimber and old growth	Pole-timber	Saplings-seedlings	Nonstocked	Total
	Percent[1]				
White pine-hemlock	1.9	1.0	0.6	--	3.5
Spruce-fir	.2	--	--	0.1	.3
Loblolly pine	--	.2	.2	--	.4
Shortleaf pine	.3	.3	--	--	.6
Virginia pine	1.0	2.9	1.4	--	5.3
Pitch pine	.1	1.3	--	--	1.4
Oak-pine	3.3	4.3	1.0	--	8.6
Oak-hickory	38.9	24.2	5.9	.6	69.6
Chestnut oak	3.3	.6	.3	.2	4.4
Elm-ash-cottonwood	--	.2	--	--	.2
Maple-beech-birch	3.9	1.2	.2	.4	5.7
Total	52.9	36.2	9.6	1.3	100.0

[1] Percent of area.

Table 7.--Diversity of forest types by condition classes of stands for the Pisgah National Forest in North Carolina

Forest types	Condition classes of stands				
	Sawtimber and old growth	Pole-timber	Saplings-seedlings	Nonstocked	Total
	Percent[1]				
White pine-hemlock	1.2	1.2	--	--	2.4
Spruce-fir	--	--	--	1.2	1.2
Loblolly pine	--	--	--	--	--
Shortleaf pine	--	--	--	--	--
Virginia pine	--	1.5	--	--	1.5
Pitch pine	1.1	6.0	--	--	7.1
Oak-pine	4.8	--	--	--	4.8
Oak-hickory	50.1	20.3	2.6	1.5	74.5
Chestnut oak	4.1	1.6	--	--	5.7
Elm-ash-cottonwood	--	--	--	--	--
Maple-beech-birch	2.8	--	--	--	2.8
Total	64.1	30.6	2.6	2.7	100.0

[1] Percent of area.

Table 8.--Diversity of forest types by condition classes of stands for the Nantahala National Forest in North Carolina

Forest types	Condition classes of stands				
	Sawtimber and old growth	Pole-timber	Saplings-seedlings	Nonstocked	Total
	Percent[1]				
White pine-hemlock	--	--	--	--	--
Spruce-fir	--	--	--	--	--
Loblolly pine	--	1.7	--	--	1.7
Shortleaf pine	--	--	--	--	--
Virginia pine	--	--	--	--	--
Pitch pine	--	1.2	--	--	1.2
Oak-pine	5.1	--	2.5	--	7.6
Oak-hickory	43.6	15.7	4.1	--	63.4
Chestnut oak	12.4	2.9	3.2	--	18.5
Elm-ash-cottonwood	--	--	--	--	--
Maple-beech-birch	6.1	1.5	--	--	7.6
Total	67.2	23.0	9.8	--	100.0

[1] Percent of area.

Each habitat, a stand condition class of a forest type, is characterized by a definitive assembly of plants and animals. Habitats are constantly changing over time; birds, mammals, reptiles, and insects come and go; temperature, nutrient and water flows, and sediment movement vary continually; the flowering and growth of plants change seasonally and annually; and the rates of mortality of plants change as the community changes (sec. 3.1). We cannot anticipate very accurately all the kinds of species and the proportions of species plants and animals in a future community. We can anticipate, with an acceptable probability, that most naturally established forest types will remain in that forest type for some relatively long period of time. Over time, predictable changes will occur in most of the stand condition classes. But, unpredictable changes will occur in the proportions of most plants and animals. The kinds of dominant and codominant trees may be predicted with an acceptable probability. Thus, the most reliable basis for anticipating change is the physical changes in stand condition classes for a given forest type. For example, one can anticipate that a seedling habitat of a forest type will change to a sapling habitat of the same forest type during a predictable time. Figures 4 and 5 display these kinds of anticipated changes in the diversity of communities.

In section 2.5 we used the dynamic analytic silviculture techniques (Boyce 1977) to examine changes anticipated by natural forces unaffected by man (fig. 4). The dominant old trees are assumed to die, break, or blow down at about 290 to 310 years of age. Relatively small openings of less than 0.6 of an acre are formed. The seedling habitat (S) declines for about 30 years. Then, as the proportion of old growth (O) increases, mortality of the old trees increases the proportion of seedling habitats to less than 2 percent of the forest. Old-growth habitat increases to about 63 percent of the forest. After 170 years, each of the other habitats, other than old growth, occupies less than 10 percent of the forest.

Now we change the mode of management. The result is to increase the proportion of seedling habitats, reduce the proportion of old growth, and reduce the constraints on the distribution of habitats (fig. 5). With this mode of management, 30 percent of the area is permitted to rotate through a 200-year period and 70 percent of the area is permitted to rotate through a 100-year period. Sizes of the openings are 10 ± 2.4 acres and are interspersed so that, in time, all of the kinds of habitats are intermingled. After 170 years, the sapling habitat covers the largest area, about 26 percent of the forest. All other habitats represent 4 percent for seedlings to 18 percent for pole-10 habitats.

Opening size is as important as the rate of harvest for anticipating the diversity of habitats. The size of openings formed by harvest determines, over time, the area of each kind of habitat, old growth as well as seedling. The amount of transition area, ecotone, between habitats is determined by the combinations of rate of harvest and opening size. For a given rate of harvest, the amount of ecotone increases as opening size decreases and deviates in shape from a perfect circle. Since harvest openings are almost never circular because of streams, roads, rocks, and other variables, opening shapes are typically variable.

The interspersion of habitats is related to size of opening. If the annual rate of harvest is equal to the opening size, then only one opening is formed per year per forest type. As opening size declines from the annual rate of harvest, the number of openings per year increases and dispersion of habitats increases. If opening size becomes relatively small, less than about 3 acres, the forest manager may choose to cluster the openings to reduce both the cost of road construction and the movement of sediment (Boyce 1977, page 16). The clustering of small openings reduces the dispersion of habitats in the forest. Small openings constrain the livelihood for some plants and animals, and clustering of these openings increases the constraint.

One can anticipate the diversity of communities for an infinite number of other modes of management by changing the rates of harvest and the sizes of openings. More detail is given by Boyce (1977, 1978).

5. HOW TO RELATE DIVERSITY TO MULTIPLE BENEFITS

5.1 The Integration of Diversity and Benefits

In this section we describe how the relationships of diversity and benefits may be integrated to simultaneously analyze, estimate, and specify the consequences of alternative plans for multiple benefits.

From the theory for multiple benefits (Boyce 1977, In press), the proportional distribution of habitats determines the kinds of multiple benefits available from any specified forest area. The relative amount of a benefit may be estimated by algorithms scaled from 0 to 1 (figs. 1, 2, and 3). The algorithms for benefits are independent of each other but are totally dependent on the spatial and temporal diversity of habitats.

The diversity of habitats can be used to integrate benefits and to simultaneously examine the consequences of management actions. For the example used in previous sections (secs. 2.5 and 4.2), one can consider how no harvest of timber changes the diversity of seedling, sapling, pole-6, pole-8, pole-10, mature timber, and old-growth stands (fig. 4). And, one can consider how these changes affect the relative amounts of timber harvested; the relative livelihood for squirrel, deer, and bluebirds; and the relative amounts of sediment moved (fig. 10). Since no timber is harvested, the potential timber index (T) is zero. The livelihood for deer (D) declines as the proportion of seedling habitat declines during the first 30 years. With an increase in the mortality of old trees, deer browse increases and the livelihood for deer increases to about 0.12. As the proportion of hard mast-producing trees increases, the livelihood for squirrels (Q) increases to 1 by year 50 and remains at this level for about 32 years. After year 80, the livelihood for squirrels declines as the dominant trees exceed the ages for producing large amounts of mast (U.S. Dep. Agric., Forest Service 1971).

Without timber harvesting, a reduction in open areas for bluebirds (L) to feed and nest reduces their livelihood to zero. And, since no roads are being constructed, increased sediment movement (I) is also zero. (Some sediment movement occurs, of course, under natural conditions.) The index (I) is a relative measure of the increased movement of sediment in relation to road construction.

Now, we change the mode of management to bring about the distribution of habitats described in figure 5 and in section 4.2. The availability of benefits (fig. 11) is now different from that for no timber harvest (fig. 10). The potential timber index (T) increases to about 0.75 of the maximum; the livelihood for deer (D) increases to about 0.70 of the maximum; the livelihood for squirrel (Q) increases to and remains at about 0.75 of the maximum; and the livelihood for bluebirds (L) increases to about 0.65 of the maximum. Sediment movement (I) increases to about 0.75 of the acceptable limit.

In this way, the diversity of plant and animal communities can be related to the suitability of a specific land area to meet overall multiple-use objectives. The objective for multiple-use management is not to produce so much timber, beef, water, game, recreation, hunting, fishing, and wilderness experience. Rather, the objective becomes a single goal, one of the various possible states of forest organization. For an interval of time the goal is to bring about the state of forest organization which determines a certain diversity of habitats and, thus, provides a biologically possible and desirable combination of benefits. This goal is biologically possible, physically attainable, and economically feasible.

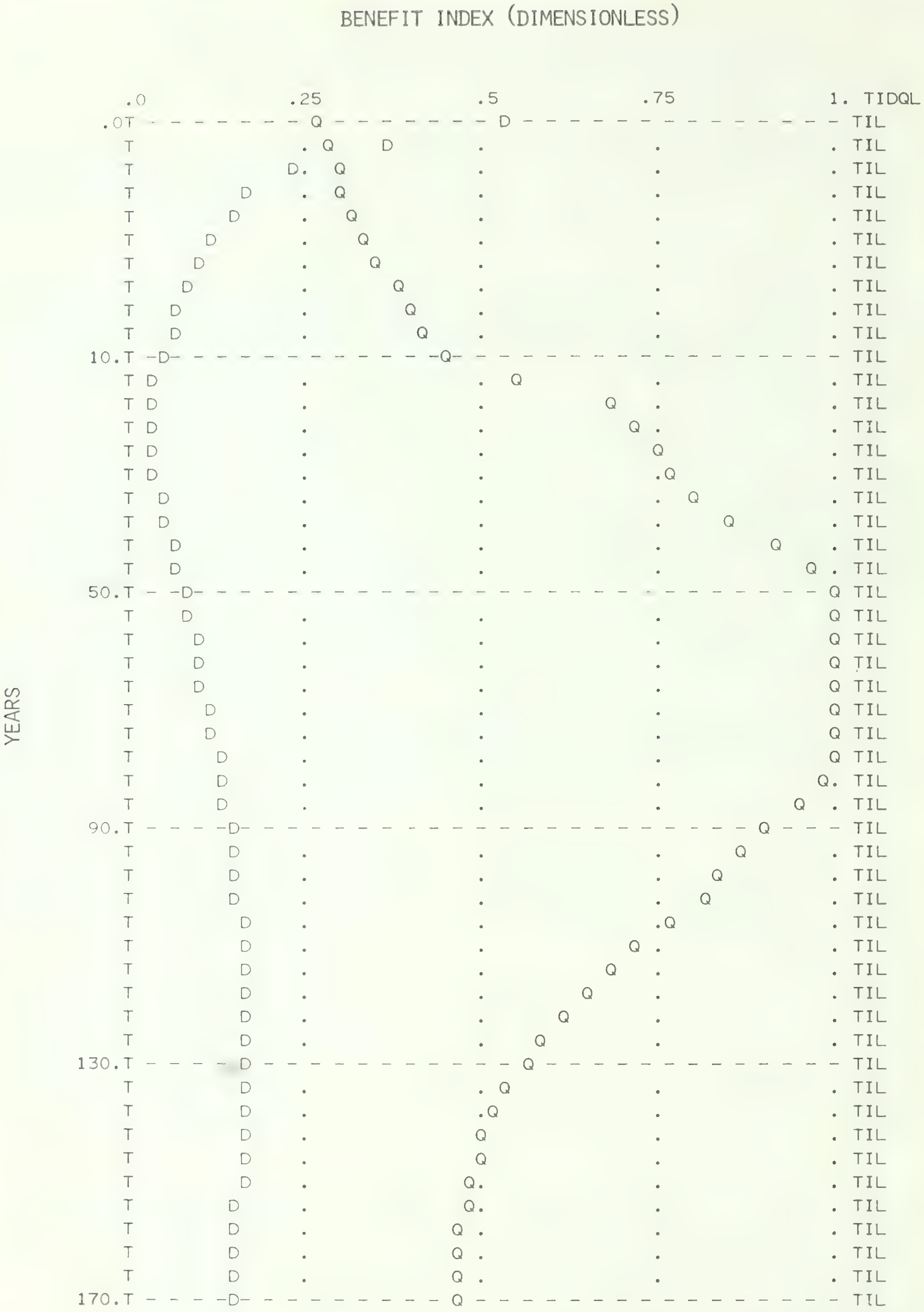

Figure 10.--When no timber (T) is harvested, some benefits such as the livelihood for deer (D), bluebirds (L), and, in time, squirrel (Q), are constrained. The relative amount of constraint of the habitats from complete randomness is indicated by the rising constraint quanta (*) for habitats (fig. 4).

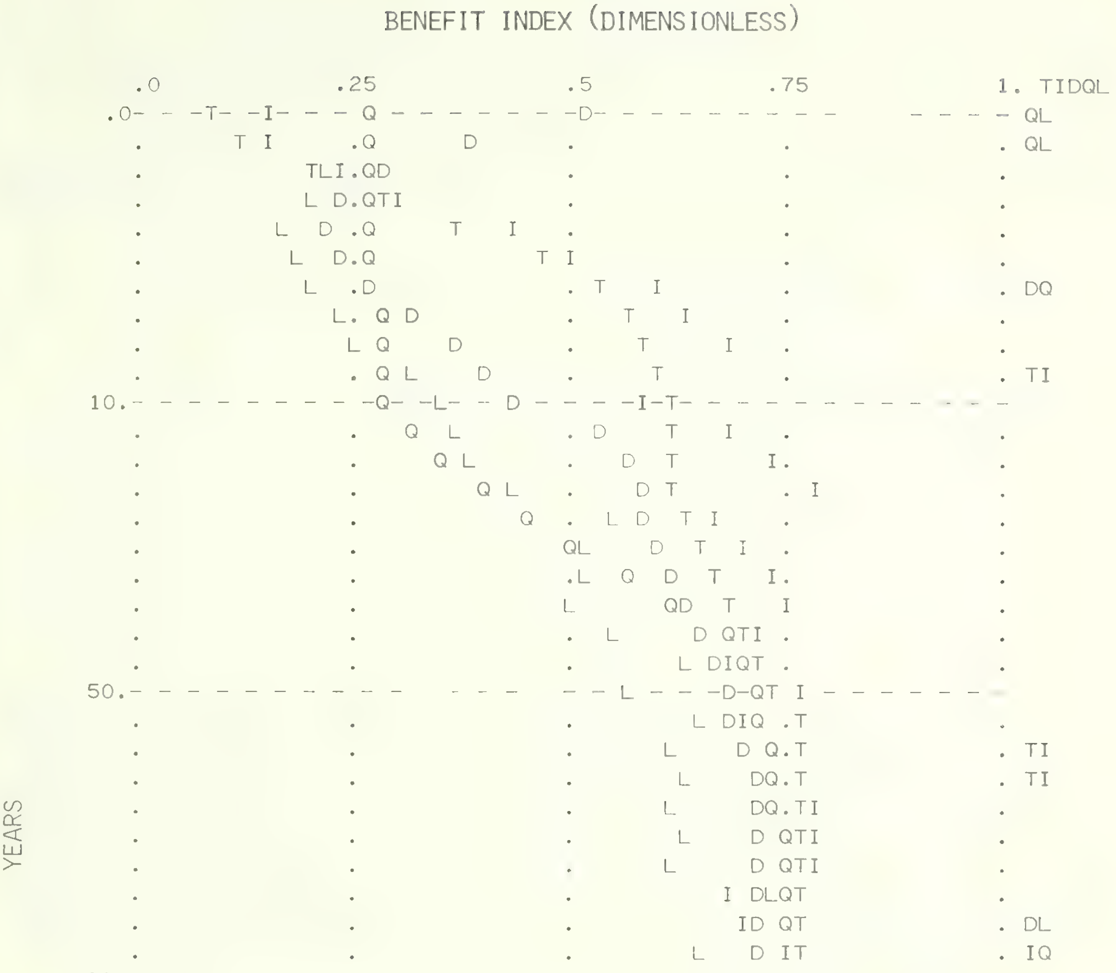

Figure 11.--Indices for eight benefits and one impact for a moderate mode of management. T = potential timber index; I = sediment; D = deer habitat; Q = squirrel habitat; L = bluebird habitat. This illustration is modified from figure 2 (Boyce 1977). Indices are plotten annually for the first 10 years, then at 4-year intervals. Letter groups at the top of the graph indicate coincident indices; the first letter of each group appears on the plot.

The organization of the forest (the distribution of habitats) is controlled by scheduling the rates of harvest and the size of openings formed by harvesting (Boyce 1977, 1978). Two or more rotation periods may be superimposed so that old growth and young stands are closely intermingled and, over time, interchangeable. Thus, age classes of stands are distributed in varying proportions from 1 year to some very old age such as 300 years. The distribution of habitats is brought to one of a large number of steady states. At any one of a number of steady states, a livelihood for most, if not all, endemic organisms is possible and certain combinations of benefits are available.

In this way, plans can include the results of integrated analyses and anticipated consequences of alternative modes of management.

5.2 Monitoring Diversity for Multiple-Use Objectives

The purpose for monitoring diversity is to acquire information that is useful for making decisions about the congruence of an implemented plan and the real forest. By congruent we mean that actions selected under the plan direct the biological systems to achieve the desired state of forest organization (Boyce, In press). An important way to monitor diversity is to use periodic inventories of the forest to compare the diversity of elements in the real forest with those anticipated by the plan.

The period for forest management is separated into management intervals, typically 10 years. At the beginning of each interval the forest is inventoried for those elements of diversity that indicate the state of organization. The plan anticipates a future state of forest organization; for example, the diversity of habitats (fig. 5). Data from these inventories are used first to examine the congruence of the plan and the habitats. For example, one may use a chart (fig. 6) to compare the proportional distributions of seedling, sapling, and other habitats at time 10 years in the plan (fig. 5) with data from the inventory. Reasons for differences are determined and, if necessary, adjustments are made in the plan (Boyce 1977, page 19).

During the 10-year management intervals, information from research, observations, and experience are used to adjust the algorithms for benefits to fit the specific forest that is under management. For example, the shape of the curves in figures 1, 2, and 3 may be changed to agree with new findings. An additional algorithm may be added for the computation of a combined index (sec. 2.2). New yield tables may be developed for timber. Algorithms may be developed for additional benefits, including streamflow, social values, and economic cost and returns. The new inventory and the revised algorithms are inserted into the plan; for example, one of the DYNAST modes of management (Boyce 1977, 1978). The anticipated combinations of benefits for the next 10 to 100 years is examined. The benefits are then evaluated in terms of consumer attitudes.

New attitudes and desires for social and economic benefits may require a change in the mode of management. These changes are made by adjusting the rates of timber harvest and the sizes of openings for each forest type to bring about the desired combination of benefits (Boyce 1977). For the next 10 years, the management goal is to change the present state of forest organization toward that anticipated by the revised plan.

Near the end of each management interval, the processes of inventory, algorithm adjustment, and change in management mode are repeated. In this way, monitoring provides information that is useful for making management decisions about the congruence of the plan and the real forest. The multiple-use objectives are kept congruent with consumer attitudes for social and economic benefits.

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The National Forest Management Act of 1976 (90 Stat. 2949; 16USC1600) chartered a new direction for the Forest Service. Previously, no regulations existed that provided for a diversity of forest plant and animal communities and the preservation of indigenous tree species, nor were consumer attitudes regarding social and economic benefits and multiple-use of forests so clearly delineated. The Act necessitated, first of all, the development of an operational definition of "diversity" that would have a common meaning to foresters and forest managers. This Paper provides such a definition and sets forth new concepts and applications of forest management designed to bring about the improvements desired.

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Preventing Basement Leakage in Treated-Wood Foundations

by

Gerald A. Koenigshof

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Southeastern Forest Experiment Station

December 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

Preventing Basement Leakage in Treated-Wood Foundations

by

Gerald A. Koenigshof, Chief Wood Scientist
Forestry Sciences Laboratory
Athens, Georgia

Abstract.—Some of the traditional means of preventing basement leakage are ineffective. Far more important than the use of sealants and drain tile are the control of water through effective surface drainage and the maintenance of soil permeability for proper subsurface drainage. Although the methods described in this report are intended for use with treated-wood foundations, they will improve the performance of foundations built with other materials.

KEYWORDS: Basement construction, waterproofing, drainage, moisture control.

Many homes are now being built with foundation walls constructed of pressure-treated wood instead of masonry block or concrete.[1] [2] Basements (fig. 1) with pressure-treated wood walls have the advantages of being less expensive to construct, easier to insulate, more comfortable to live in, easier to finish off, faster to build, and more easily erected in wetter and colder weather than conventional systems. A unique feature of this new system is its ability to resist leaking and to remain dry without the use of perimeter drain tile, cement parging, or asphalt coating included in other systems. This Paper shows why pressure-treated wood foundations do not leak, even though these traditional methods for preventing leakage are not used.

CONTROLLING WATERFLOW

In preventing basement flooding, directing rainwater flow away from the house is more important than sealing basement walls or providing elaborate or complicated drainage systems.

In 1966 I studied the causes and prevention of basement leakage for the National Association of Home Builders (NAHB)[3] and was impressed with the importance of controlling water flow. I studied over 130 houses that had a history of leakage. Many of these houses had perimeter drain tile, walls parged with cement plaster, and asphalt coatings on the outside wall surfaces. Nevertheless, these houses leaked. At the same time, some home builders reported that thousands of their houses never leaked, even though these conventional techniques for preventing leakage were absent. From this study we learned how to build basements with masonry block or cast-in-place concrete walls that won't leak.

In the late 1960's I was in charge of a project to develop treated-wood foundations. In designing the treated-wood foundation, we incorporated concepts of leak prevention which we had learned from the study of basement leakage. As a result, we rarely hear of basement leakage with wood foundations. I estimate that about 30,000 treated-wood foundations have been built in the United States and Canada, and I have heard of only seven houses having leaking problems, all of which have since been corrected. The "All-Weather Wood Foundation System: Design,

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[1] American Plywood Association. 1976. The all-weather wood foundation: Why, what and how. 35 p. Am. Plywood Assoc., Tacoma, Wash.

[2] National Forest Products Association. 1975. All-weather wood foundation system: Design, fabrication, and installation manual. 74 p. Natl. For. Prod. Assoc., Washington, D. C.

[3] A pilot study of the causes, prevention, and correction of basement water leakage problems, by Natl. Assoc. Home Build. Res. Found., June 1966.

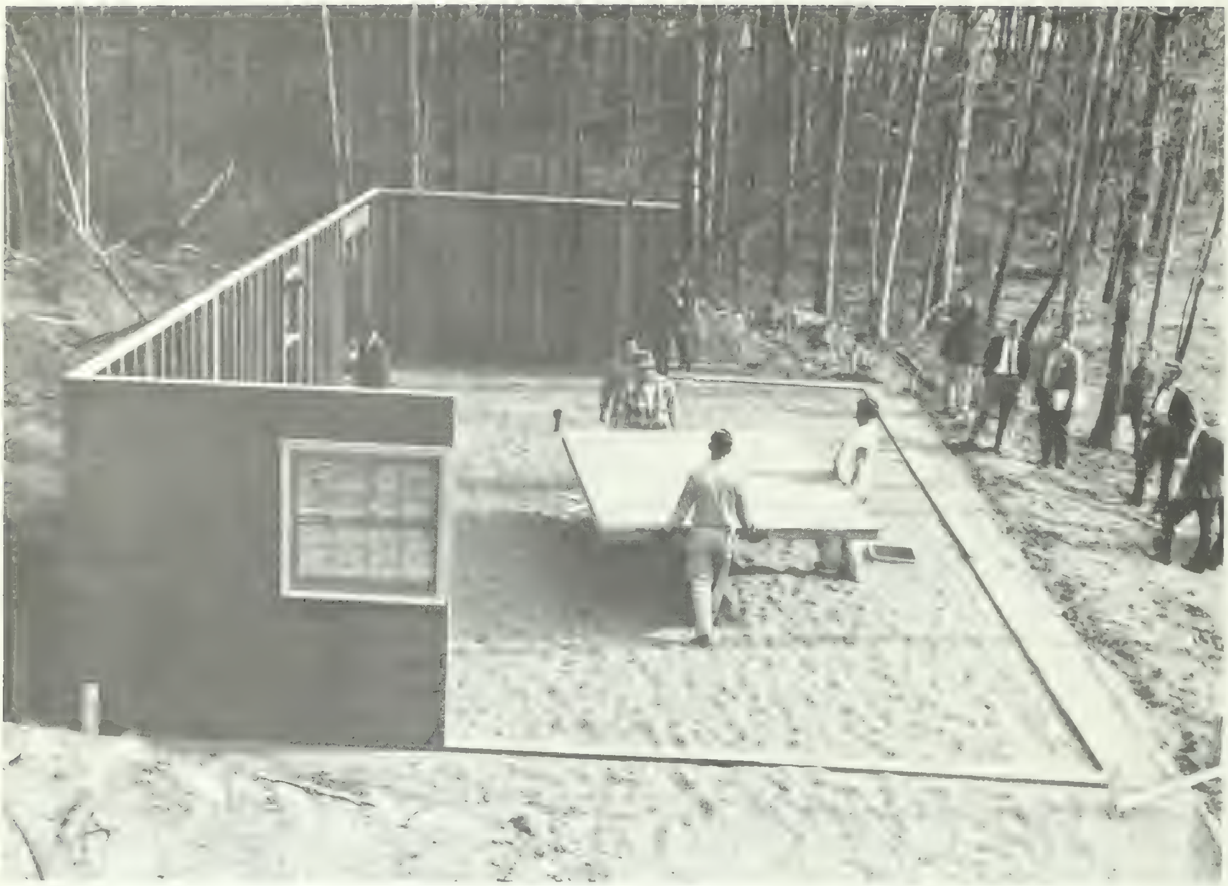

Figure 1.—Basement treated-wood foundation under construction.

Fabrication, and Installation Manual" (*see* footnote 2), published by the National Forest Products Association, contains recommended practices for building a leak-free treated-wood foundation.

To understand how to build a house that will not leak, we must consider two types of drainage: (1) drainage above grade, or surface drainage; and (2) drainage below grade, or underground drainage.

SURFACE DRAINAGE

Proper Grading

In the NAHB study, 85 percent of the cases of basement leakage were found to occur after rainstorms. The single most important factor in preventing basement leakage, therefore, is getting rainwater or water from melting snow away from the house before the water can enter the ground. Of all the techniques used to prevent basement leakage, proper grading is probably the best; certainly, its importance cannot be overemphasized. The surface of the ground around the house should be sloped away from the house for a distance of 8 to 10 feet. The slope should be at least ½ inch per foot; however, an inch per foot is preferable. Figures 2 through 5 illustrate methods of grading building lots to divert water away from the house.[4] Figure 2 shows how to grade lots that have a high elevation near the rear of the lot and that slope toward the front. Figure 3 shows how to grade lots where the entire lot and surrounding lots have a gentle cross-slope. Figure 4 shows how to grade lots where the entire lot and surrounding lots have a steep cross-slope. Figure 5 shows how to grade relatively flat lots by providing drainage valley and easement near the rear-lot line.

Gutters and Downspouts

Rainwater from gutters and downspouts must also be directed away from the house. If the gutter fails or overflows, a sloping grade will get the water away from the house. Routing of downspout discharge into underground tile next to the house should be avoided because, if the tile drain becomes plugged, the entire runoff from the roof will collect outside the basement wall and cause flooding. Under these conditions, expansive soil can swell, causing leakage problems and structural damage to walls.

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[4] Reprinted from Federal Housing Administration Minimum Property Standards No. 300.

Since it is unlikely that builders will take time to design gutter and downspout systems, this aspect of preventing basement leakage is not covered in this Paper. However, for interested detailers, designers, and builders, further information on design of gutters and downspout systems may be found in "Architectural Graphic Standards"[5] or other standards on building designs.

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[5] Ramsey, Charles G., and Harold R. Sleeper. 1970. Architectural graphic standards. 6th ed. 695 p. John Wiley and Sons, New York.

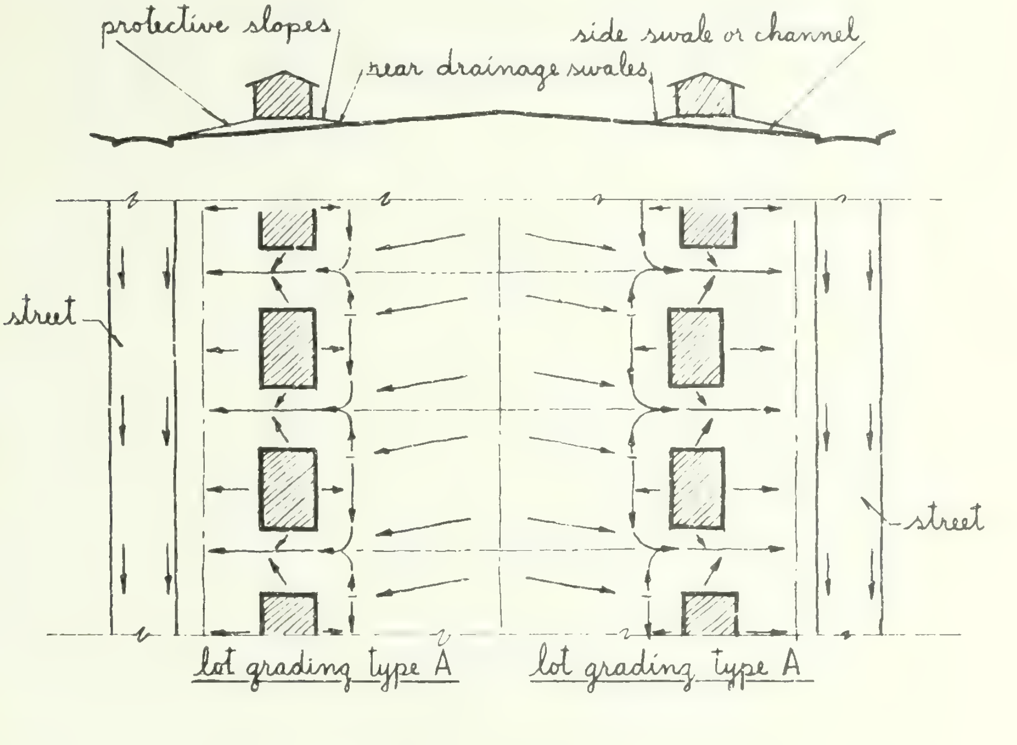


Figure 2.—Proper grading of a building lot with essentially level ground. Figure reprinted from *Federal Housing Administration Property Standards*.

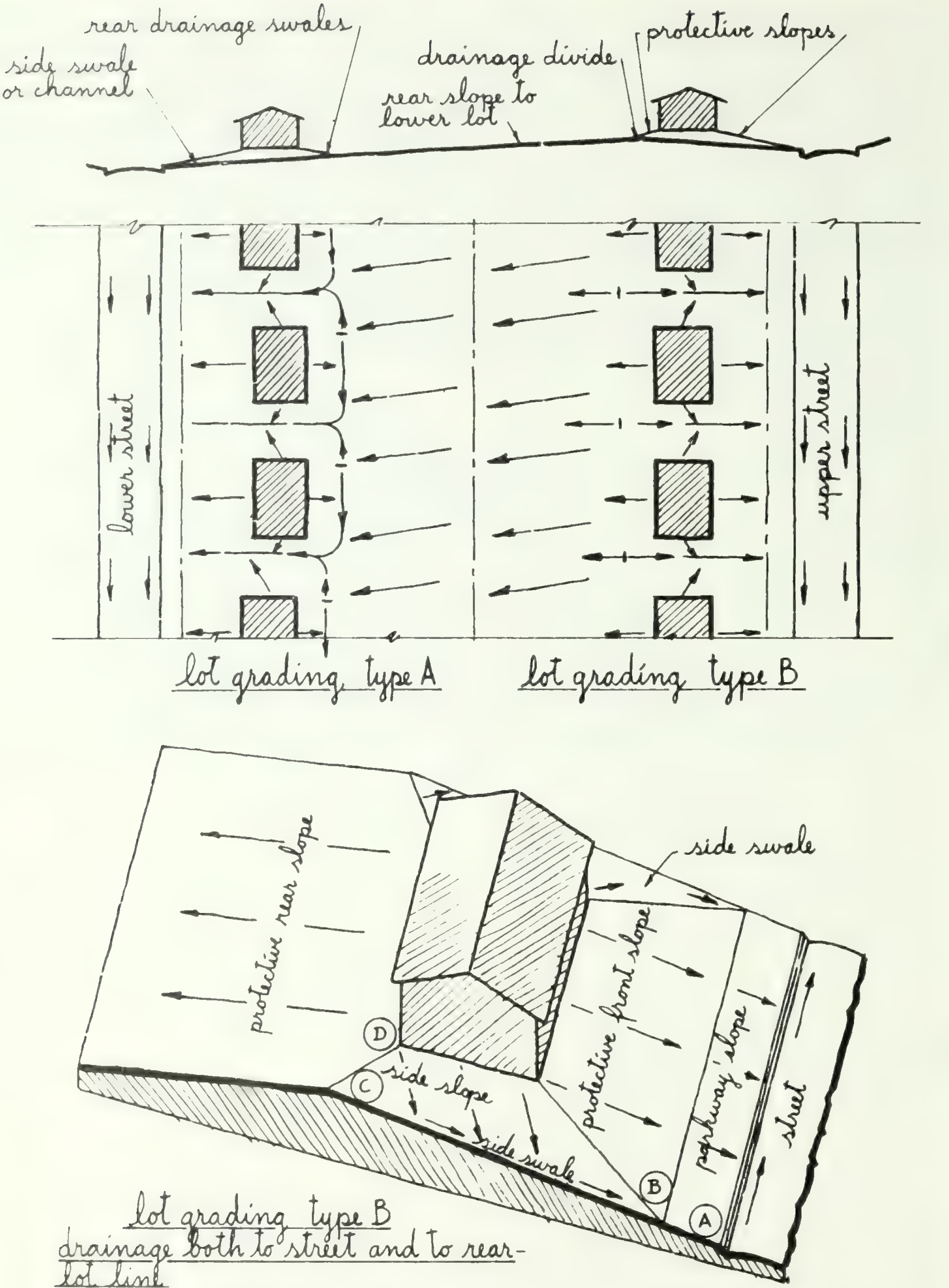


Figure 3.–Proper grading of a building lot with a gentle cross-slope. Figure reprinted from *Federal Housing Administration Property Standards.*

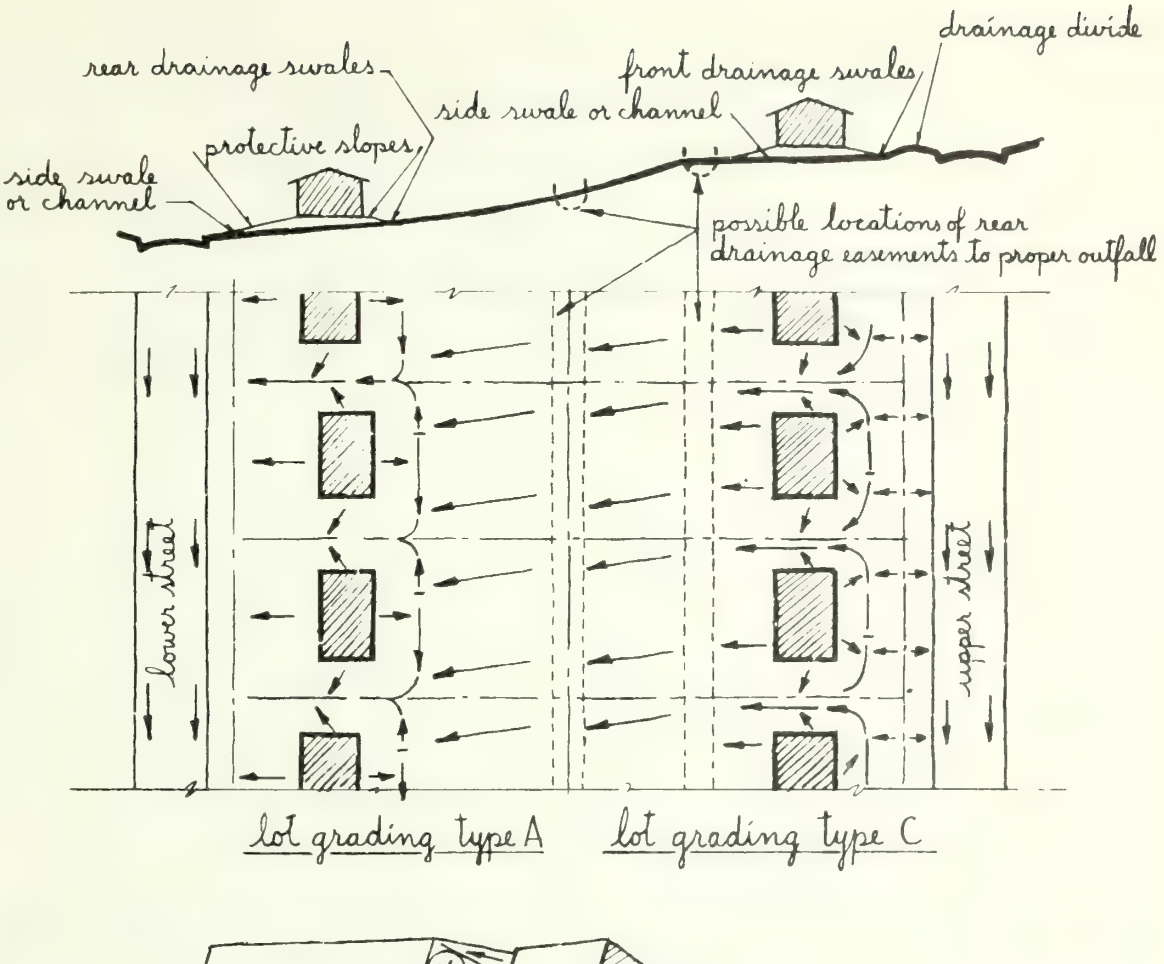


Figure 4.—Proper grading of a building lot with a steep cross-slope. Figure reprinted from *Federal Housing Administration Property Standards.*

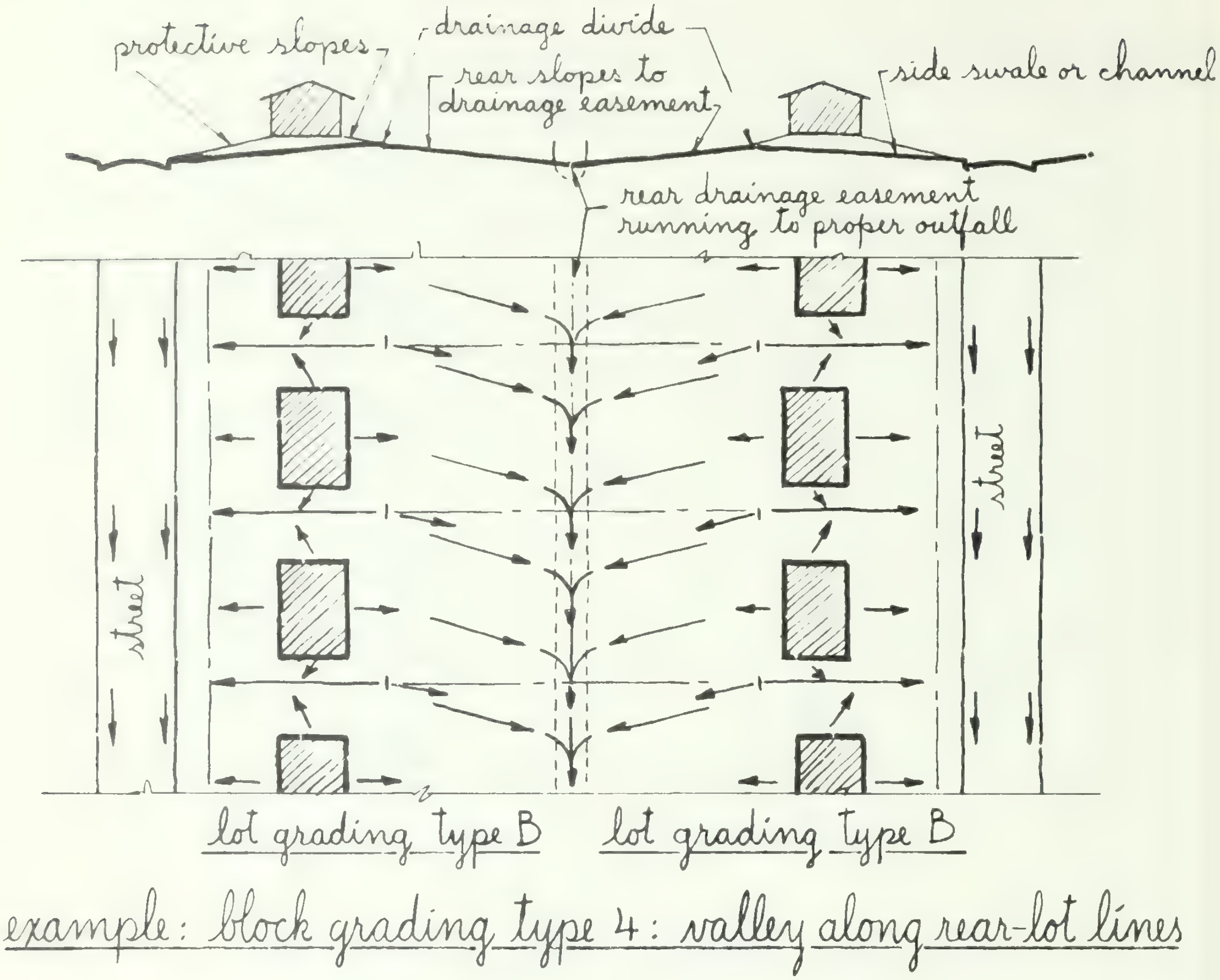

protective slopes
drainage divide
rear slopes to drainage easement
side swale or channel
rear drainage easement running to proper outfall
street
street
lot grading type B
lot grading type B
example: block grading type 4: valley along rear-lot lines

Figure 5.—Proper grading of a building lot with level ground, using rear drainage easement. Figure reprinted from *Federal Housing Administration Property Standards.*

Problems in Surface Drainage

Poor surface drainage can be aggravated by flowerbeds, depressions under porches, depressions due to settling backfill, window wells, or any other conditions that cause water to collect next to the foundation wall. On the other hand, large roof overhangs help to reduce chances of water collecting near the foundation wall.

In addition to rain or melting snow, water from an overflowing stream or river, or water from an upland waterway (flash flood) may move in when heavy storms occur; the result is frequently a flooded basement. Obviously then, houses should not be constructed on flood plains or in natural drainage areas. Many of these potential flood areas have been located and defined; both the Soil Conservation Service and the U.S. Geological Survey provide information on flood plain areas in the United States.

In summary, proper grading is the most reliable method of controlling surface water and preventing basement leakage.

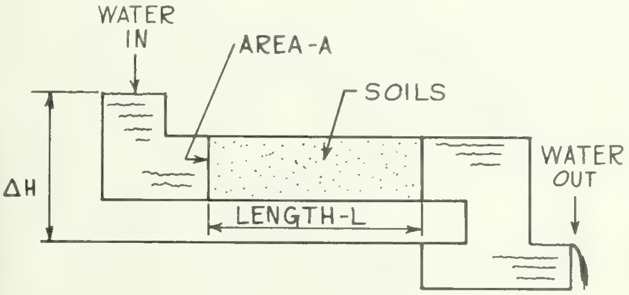
SUBSURFACE DRAINAGE

How Water Behaves in Soils

To understand control of water below grade, it is necessary to know how water moves through or is retained by soils. This knowledge is the key to understanding why some basements leak, even though all of the usual techniques for preventing leakage have been used; this behavior also helps to explain why some basements never leak even though apparently no measures have been taken to prevent leaks. Water movement in soils explains why treated-wood foundations, which do not use perimeter drain tile, can have an extremely low incidence of leakage.

Darcy's Waterflow Study

A French physicist named Darcy studied the flow of water in soils. In his test setup (fig. 6), Darcy placed a sample of soil between two reservoirs of water. The level of water in one reservoir was higher than the level in the other reservoir by an amount Δh. For a length of soil (L) and cross-sectional area (A), Darcy measured the flow of water (Q) through the soil. He found that the flow of water through the soil was directly proportional to the area (A) and the hydraulic gradient ($i = \Delta h/L$). The constant of proportionality (k) is called the coefficient of permeability. Figure 7 provides a sample computation. If it is assumed that the cross-sectional area of the soil is 1 square foot, the length of the soil sample 3 feet, and the head loss (Δh) 3 feet, then the flow of water (Q) through the soil is simply equal to k, the permeability. For various types of soil, it is possible to see how much water will pass through in 1 day. For each square foot of coarse clean sand, gravel, or crushed stone, several thousand cubic feet of water can move through 3 feet of soil with a hydrostatic head of 3 feet. On the other hand, if this clean, coarse soil becomes infiltrated with silt or clay, its capacity to move water will decrease to less than 100 cubic feet per day. If soil is a clay or solid rock, then essentially no water moves through.



$$Q = kiA$$

$$i = \frac{\Delta H}{L}$$

Q = FLOW OF WATER IN FT^3/DAY
k = SOIL PERMEABILITY IN FT/DAY
i = HYDRAULIC GRADIENT
A = CROSS-SECTIONAL AREA IN FT^2
ΔH = HEAD LOSS IN FT
L = DISTANCE WATER MOVES THROUGH SOIL IN FT

Figure 6.—Darcy's equation for waterflow through soil.

$$A = 1\ FT^2$$
$$L = 3\ FT$$
$$\Delta h = 3\ FT$$
$$i = \Delta h/L = 1$$
$$Q = k \times 1 \times 1 = k$$

TYPE SOIL	k FT/DAY	Q FT^3/DAY
CLEAN GRAVEL	22,500	22,500
CLEAN COARSE SAND	5,100	5,100
CLEAN FINE SAND	36	36
SILTY SAND AND GRAVEL	15	15
CLAY	0.0003	0.0003

Figure 7.—Computations for waterflow through various soils using Darcy's equation, assuming a cross-sectional area of 1 square foot, length of soil of 3 feet and a head loss of 3 feet.

Figure 8 shows a house built where the soil is well drained and has a high permeability. Even if no techniques to prevent leakage were used, a basement built on such a site would probably never leak, for rainwater would rapidly penetrate the soil to the water table. From Darcy's equation, we can see that the soil has a built-in water drainage system. This situation is typical in sandy soils like those in parts of Florida, where water from a 2-inch rainstorm disappears almost as quickly as it falls. Of course, the water table will rise, and in Florida or any other such area, this high water table may prevent the building of basements.

Figure 9 illustrates a house built where the soil is poorly drained and has low permeability. A basement built on such a site would probably leak even though a builder employed all of the usual techniques to prevent leakage. Since rainwater cannot easily penetrate this soil, water collects on top of the ground. The water runs along the surface toward the basement on one side of the house. Because the builder has backfilled this area with sand, the water rapidly penetrates the backfill, establishing a hydrostatic head outside the wall. Overflowing gutters (or the absence of gutters) will contribute to the problem. The surrounding clay is essentially impervious,

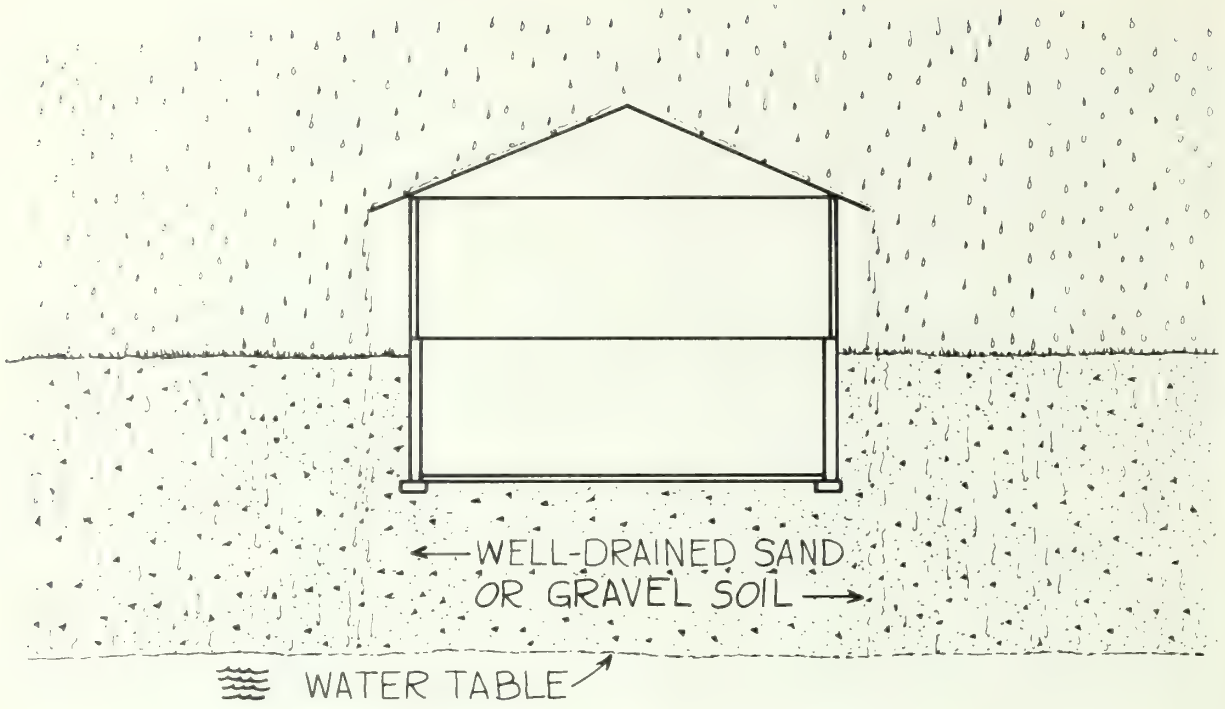


Figure 8.—Foundation built in well-drained soil is not likely to leak.

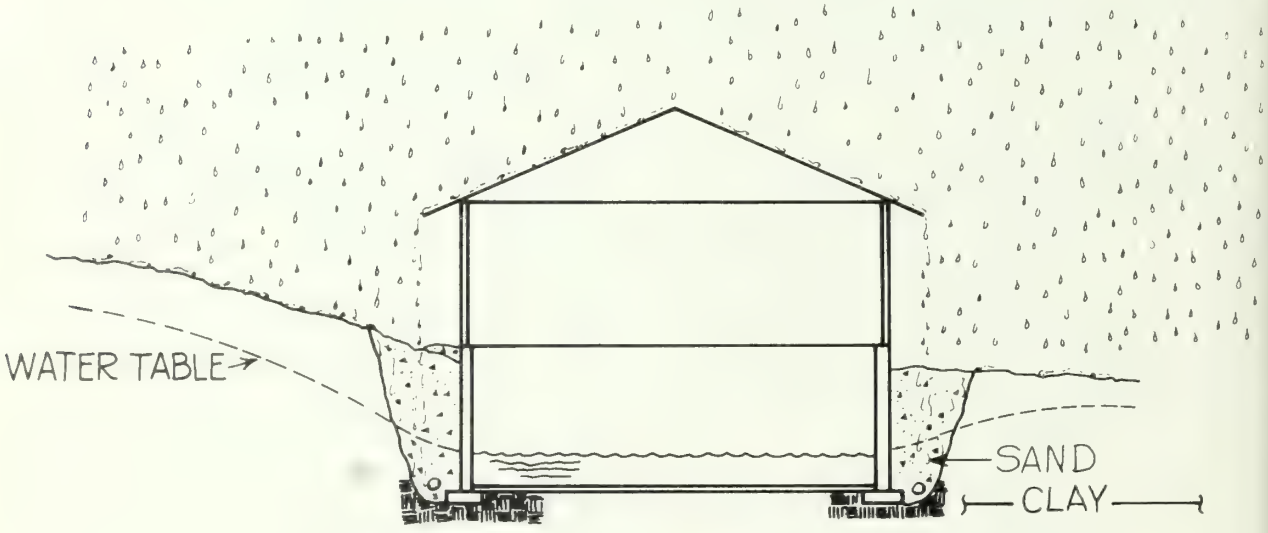


Figure 9.—Conditions that lead to basement leakage.

and no water can escape except through cracks or holes in the basement walls. If the perimeter drain tile fails (or if its capacity is inadequate), this basement will surely flood. Where concrete footings are used, they rest directly on the clay soil and block any chance for the water to escape to a reservoir under the basement floor. A deep, porous fill under a floor slab might easily hold all the rainwater penetrating the backfill, but the concrete footing will block this potential source of drainage.

HOW TO MAKE A BASEMENT LEAKPROOF

Figure 10 shows how to build a leakproof basement on the site shown in figure 9 with masonry-block walls, cast-in-place walls, or treated-wood walls.

BACKFILL

In figure 10, the surface has been properly

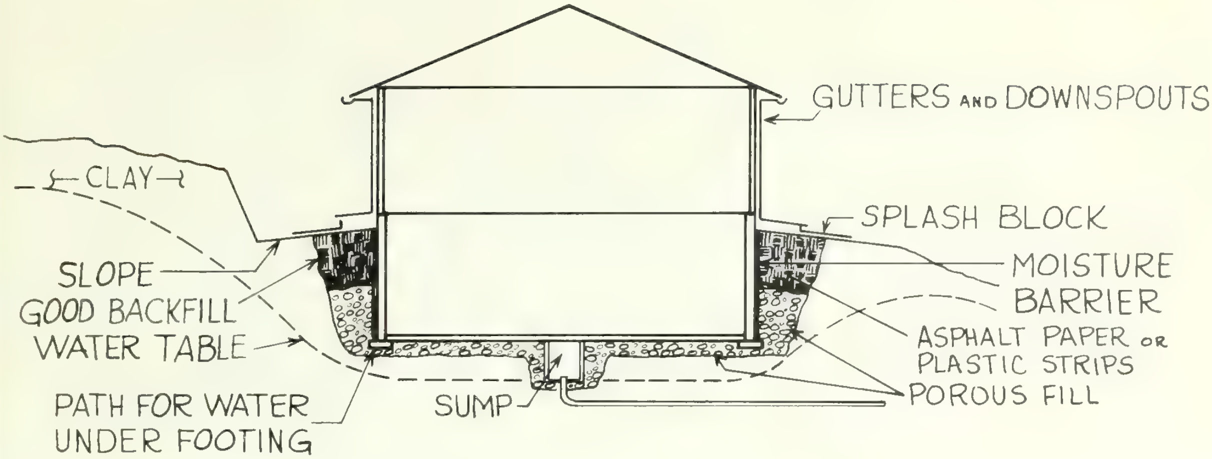


Figure 10.—Construction features that prevent basement leakage.

graded and gutters have been added to get water away from the house. The backfill near the footing is crushed stone or washed gravel, which is so permeable, according to Darcy's equation, that it will transport thousands of gallons of water per hour. Installing this backfill is easier and more foolproof than installing footing tile. Asphalt paper or strips of plastic laid loosely over the gravel or crushed stone will let water through but prevent silts or clays from infiltrating and plugging the porous material below. The area near the surface should be backfilled with soil containing some clay to prevent water from entering the backfill. To eliminate depressions that could hold ground water, the surface should be covered with moist, easily compacted soil. If backfill contains organic material, chunks of frozen earth, or construction debris, settling will eventually occur and a collection spot for water will be formed next to the wall.

DRAIN TILE

Any water that collects outside the wall must be removed. Builders have traditionally used perimeter drain tile to carry away such water, but this tile may fail to function because of improper installation or infiltration by silts, clays, or fine sands. Once a tile system has been covered with backfill, it is inaccessible for repair or maintenance without completely reexcavating. In the NAHB study we found that some builders, who had no basement leakage problems and who did not use drain tile, relieved water pressure outside basement walls by providing a system of weep holes through the basement walls to a point beneath the basement slab. These builders used pipe, angle irons, or special concrete blocks with weep holes, or they formed channels in the top of concrete footings to relieve water pressure outside walls. They filled in 4 to 6 inches of gravel or crushed stone under the floor slab to receive water coming through the weep holes. A plastic vapor barrier was placed over this fill to prevent moisture from moving upward into the floor. In wood foundations, the gravel footing is a natural drain to the porous fill under the slab.

SUMPS

The fill under the slab is drained to a sump that maintains the water table well below the floor-slab elevation. In some cases, builders used a collection pit (with no access through the basement slab) at the low point of discharge (fig. 11). The positive point of discharge should preferably be the storm sewer, the sanitary sewer, or a point above the ground surface if the grade permits. In some communities local laws prohibit connection of sumps, downspouts, footing drains, or under-floor basement drains to sanitary sewers. If this is the case, there should be a drain or pump to the surface. The only other alternative is to drain or pump water to an underground seepage pit or drain field which can adequately absorb the water. Unfortunately, in many types of soils, especially clay soils, the latter method is usually impractical because when drainage is most needed, the seepage pit is least likely to work.

A better solution is to provide a sump with an access opening through the basement floor (fig. 12). Builders can use three drainage methods from this sump: (1) An automatic float or pressure-actuated sump pump can be installed which goes into operation when the water level in the sump reaches a point

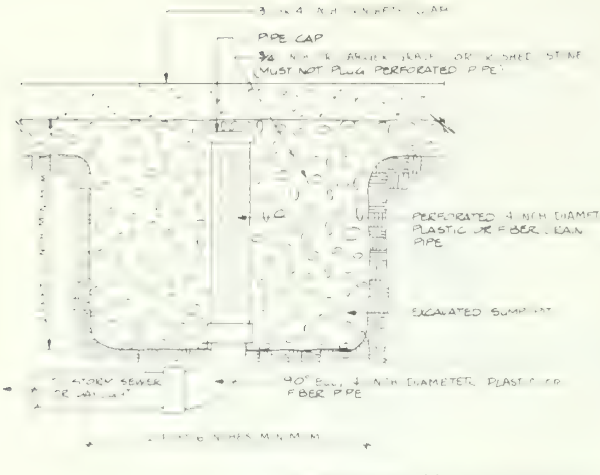

3- OR 4-INCH CONCRETE SLAB
PIPE CAP
3/4-INCH CRUSHED GRAVEL OR CRUSHED STONE (MUST NOT PLUG PERFORATED PIPE)
PERFORATED 4-INCH DIAMETER PLASTIC OR FIBER DRAIN PIPE
EXCAVATED SUMP PIT
TO STORM SEWER OR DAYLIGHT
90° ELL, 4-INCH DIAMETER PLASTIC OR FIBER PIPE
6 INCHES MINIMUM
NOTE: VERTICAL PIPE MAY BE EXTENDED THROUGH SLAB WITH A CLEAN-OUT PLUG IN FLOOR

Figure 11.—Sump for medium- to well-drained soils.

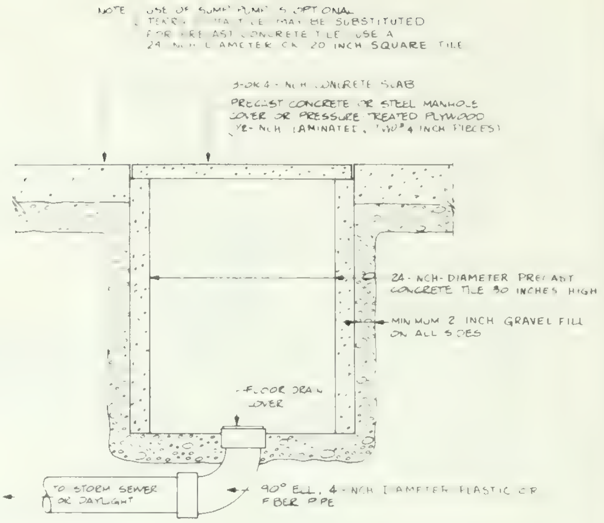

NOTE: USE OF SUMP PUMP IS OPTIONAL. TERRA COTTA TILE MAY BE SUBSTITUTED FOR PRECAST CONCRETE TILE. USE A 24-INCH DIAMETER OR 20 INCH SQUARE TILE
3- OR 4-INCH CONCRETE SLAB
PRECAST CONCRETE OR STEEL MANHOLE COVER OR PRESSURE TREATED PLYWOOD (1/2-INCH LAMINATED, TWO 3/4 INCH PIECES)
24-INCH-DIAMETER PRECAST CONCRETE TILE 30 INCHES HIGH
MINIMUM 2 INCH GRAVEL FILL ON ALL SIDES
FLOOR DRAIN COVER
TO STORM SEWER OR DAYLIGHT
90° ELL, 4-INCH DIAMETER PLASTIC OR FIBER PIPE

Figure 12.—Sump for poorly drained soils.

several inches below the bottom of the basement slab; (2) a drain line from the sump to storm sewers, sanitary sewers, or the outside ground surface may be used; or (3) as an extra precaution, the builder can make a trough in the surface of the basement slab from the top of the sump to the sanitary drain; however, this practice is prohibited in most communities. Any of these three drainage methods (or some combination) may be used, depending on the apparent need. An advantage of a sump is that it is accessible throughout the life of the structure and can be cleaned or maintained without expensive excavating.

Many builders were startled when we said that tile drains were ineffective and should be eliminated as an unnecessary expense. However, when builders who had had basement leakage problems for many years used the leakage prevention methods for masonry walls suggested in the NAHB report, they stopped having leaky basements.

WATERPROOFING BASEMENT WALLS

Having gone into dark crawl spaces on bright, sunny days, I can testify that masonry block walls, even those that have been sprayed with asphalt, are full of holes. Daylight is clearly visible through the wall at many points. Contrary to what the average builder thinks, the general practices of "waterproofing" walls with parging (cement plaster), asphalt, or other sealants do not prevent basement leakage. Coatings made from asphalts with a high (400° to 600° F) melting point are solid at normal ambient temperatures. These asphalts are dissolved in solvents and sprayed on the basement walls. When the solvent evaporates, a rigid, solid asphalt coating is left on the wall; however, this coating (like parging) cracks wherever the wall cracks. Since all masonry and cast-in-place concrete basement walls settle and consequently crack, openings that will let in water must be expected. Although all types of basement walls are subject to cracking, wood foundation walls can move substantially without cracking, thus reducing the risk of leaks.

On some walls, plastic film may be worth using as a water barrier, especially where the surrounding soil is poorly drained. Attached to the wall only at the top and vertical seams, plastic film will help control water. Under the force of gravity, water that enters behind the film will flow downward and out the bottom. Although it is less likely to crack than other sealants, plastic is subject to puncture and, consequently, is not a cure-all.

Sealant systems, which are both costly and time consuming to install, are not the solution to leaky basements. Again, proper grading is the more effective method of prevention.

SUMMARY

Figure 13 depicts the methods necessary for preventing basement leakage. These methods and the key to their identity on figure 13 are:

A — Check for high water table
B — Slope ground surface away from house
C — Consolidate backfill; use soil with low water permeability
D — Use plastic moisture barrier on wall
E — Provide path under wall for passage of water
F — Use a sump in soils that are poorly drained

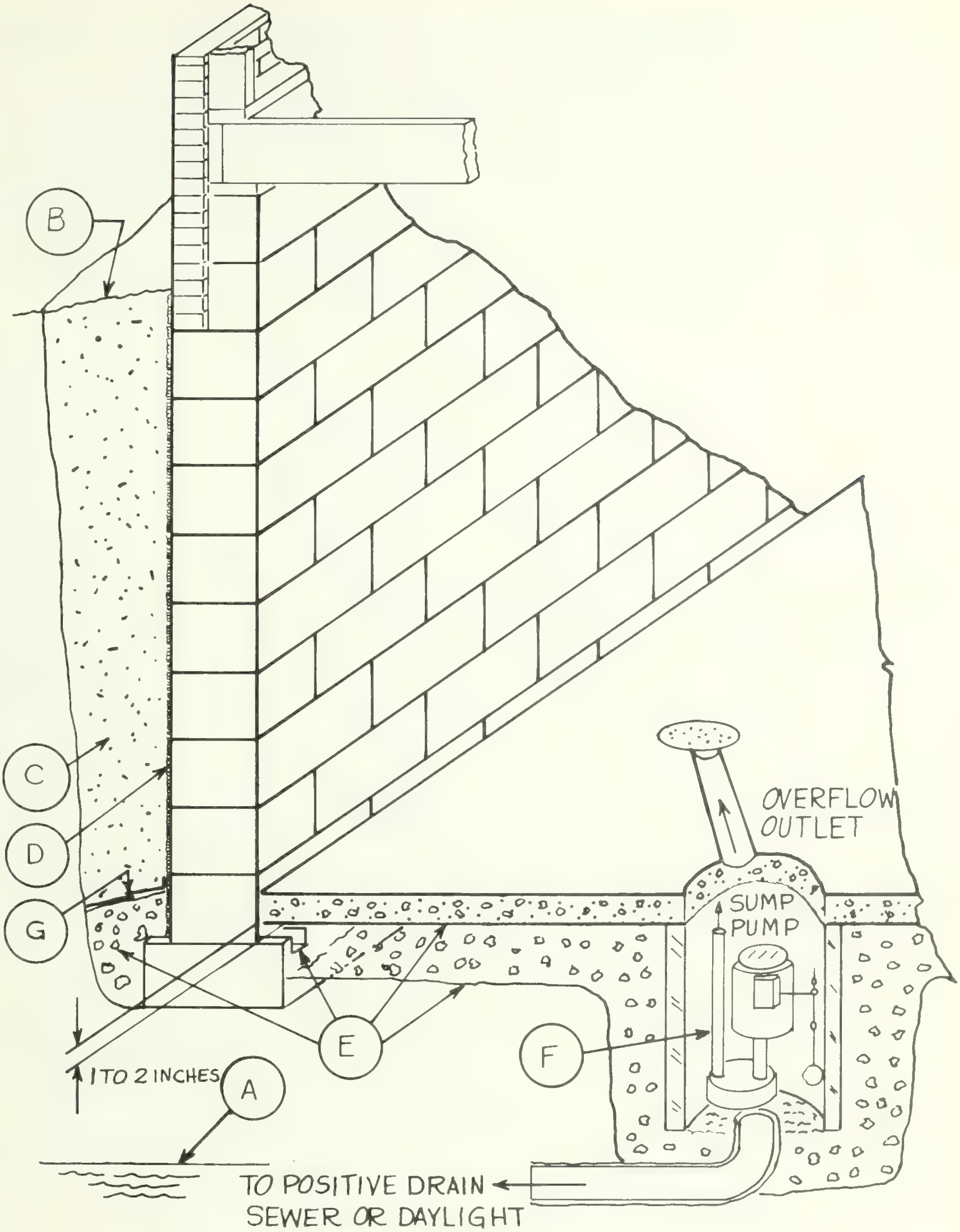


Figure 13.—Steps suggested to prevent leakage in basements with wood, masonry block, or cast-in-place walls.

G — Cover crushed stone with strips of plastic or asphalt

If the topography, ground cover (marsh-type grass, etc.), or experience in the vicinity indicates that there may be a problem with ground water or springs, the builders should bore a hole to several feet below the basement level. The height of standing water in the hole indicates the height of the ground water table at that time; even if no ground water is present, the builder should determine how high the ground water has been in the past. The U.S. Geological Survey monitors water table elevations in a number of locations; it often has useful data for builders. Obviously, a basement should not be built in natural drainage. If the elevation of the ground water table is at or near the level of the finished basement, the builder has two choices: (1) reject the site, or (2) provide a sump and pumping system with sufficient capacity to maintain the water table level below the slab.

The test boring described above will also indicate the presence or absence of clay or fine organic soils that are relatively impervious to water. If this type of soil is present, surface water will not readily penetrate downward; consequently, precautions should be taken against the likelihood of basement leakage.

Since grading is the most effective means of preventing leakage, the ground surface should be sloped away from the house for a distance of 8 to 10 feet. The slope should be at least ½ inch per foot, though some builders suggest using 1 inch per foot. When establishing this grade, the builder should allow for subsequent settling of the backfill around the basement. If downspouts are used, the water should be directed well away from the basement wall.

No more soil should be removed from the area beside the basement wall than is necessary to promote safety and provide room for construction; this restraint also minimizes excavation costs. When the backfill is placed, it should be compacted to eliminate voids in the soil that would permit water to collect outside the wall. Tamping or compacting backfill increases soil pressure against the wall, which may cause it to collapse. Some builders maintain wall braces until backfill has been placed and consolidated and for as long afterward as the sequence of construction will permit. Special care should be taken to avoid backfilling with clay chunks, which are difficult to consolidate.

If the soil does not permit good percolation, below-grade waterproofing with plastic film on the basement wall is appropriate.

To allow water that has collected outside the basement wall to flow through the wall to a point beneath the basement slab, the builder should provide a system of weep holes. These weep holes, which should be placed 4 to 8 feet apart around the foundation, may be made with pipe, angle irons, or special concrete blocks. It is necessary to make certain that the weep holes are not clogged during subsequent construction. For treated-wood foundations, a crushed-stone footing is excellent for relieving water pressure from walls (fig. 14). The builder should place 4 to 6 inches of gravel or crushed rock under the basement slab to an elevation 1 or 2 inches above the top of the footing. A plastic vapor barrier should then be placed on top of the gravel fill.

The basement floor excavation may be sloped from all directions to a single location where the sump is to be located. If gravel or crushed-rock fill is larger than pea gravel, it is probably not necessary to provide any slope since water will flow rapidly through the rock or gravel.

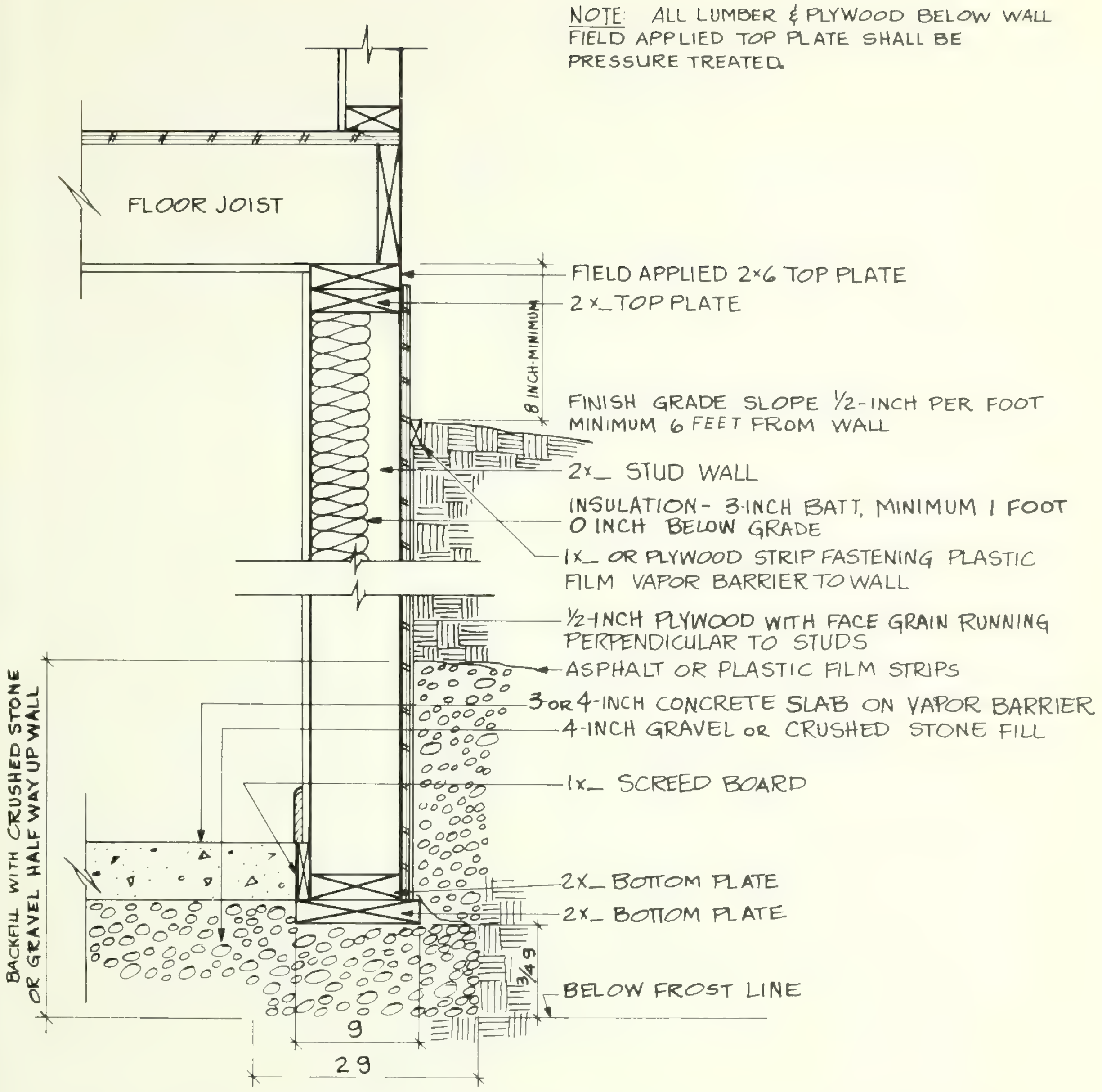
The area around the outside of the foundation wall and footing should be backfilled with gravel or crushed rock. This porous backfill should extend halfway up the wall for poorly drained soils but less than a foot for well-drained soils. The gravel or crushed stone should be covered with asphalt paper.

The sump should be constructed according to the details shown in figures 11 or 12. After estimating the probable rain intensity, hydraulic gradient, and soil permeability, the builder can calculate the size and number of sumps needed for the site. Darcy's equation provides valuable assistance in determining this need.

Good supervision at the job site is important. The construction superintendent should make sure that the workmen carefully comply with all construction details.

Figure 14 is a cross section of a typical treated-wood foundation wall.

Many builders will find it difficult to depart from their traditional reliance on drain tile and sealants; however, it should be noted that thousands of treated-wood and masonry-block foundations have been built using the water-control techniques advocated here and that these foundations are performing better than basements using some of the commonly accepted methods of preventing leakage.



NOTE: ALL LUMBER & PLYWOOD BELOW WALL FIELD APPLIED TOP PLATE SHALL BE PRESSURE TREATED.
FLOOR JOIST
FIELD APPLIED 2×6 TOP PLATE
2×_TOP PLATE
8 INCH-MINIMUM
FINISH GRADE SLOPE ½-INCH PER FOOT MINIMUM 6 FEET FROM WALL
2×_ STUD WALL
INSULATION- 3-INCH BATT, MINIMUM 1 FOOT 0 INCH BELOW GRADE
1×_ OR PLYWOOD STRIP FASTENING PLASTIC FILM VAPOR BARRIER TO WALL
½-INCH PLYWOOD WITH FACE GRAIN RUNNING PERPENDICULAR TO STUDS
ASPHALT OR PLASTIC FILM STRIPS
3 OR 4-INCH CONCRETE SLAB ON VAPOR BARRIER
4-INCH GRAVEL OR CRUSHED STONE FILL
1×_ SCREED BOARD
2×_ BOTTOM PLATE
2×_ BOTTOM PLATE
3/4 9
BELOW FROST LINE
BACKFILL WITH CRUSHED STONE OR GRAVEL HALF WAY UP WALL
9
29

Figure 14.—Basement wall constructed of treated wood incorporates design concepts to prevent basement leakage.

Koenigshof, Gerald A.
1978. Preventing basement leakage in treated-wood foundations. U.S. Dep. Agric. For. Serv., Res. Pap. SE-195, 13 p. Southeast. For. Exp. Stn., Asheville, N. C.

Some of the traditional means of preventing basement leakage are ineffective. Far more important than the use of sealants and drain tile are the control of water through effective surface drainage and the maintenance of soil permeability for proper subsurface drainage.

KEYWORDS: Basement construction, waterproofing, drainage, moisture control.

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MULTIRESOURCE INVENTORIES--
A Technique for Measuring Volumes in Standing Trees

by

Noel D. Cost

December 1978

Southeastern Forest Experiment Station
Asheville, North Carolina

MULTIRESOURCE INVENTORIES--

A Technique for Measuring Volumes in Standing Trees

by

Noel D. Cost, Resource Analyst
Asheville, North Carolina

ABSTRACT.—Procedures for measuring standing trees in forest surveys in the Southeast are described. Field tally sheets and data processing equations are provided.

KEYWORDS: Biomass, mensuration, forest survey, volume tables.

Mensurationists have long recognized the advantage in taking upper-stem measurements of sample trees when determining volumes or preparing volume tables. Until the 1960's, the only practical ways of obtaining upper-stem dimensions were ocular estimation, climbing, or felling of trees, but that problem was solved by the development of several satisfactory dendrometers. Despite these advances and the obvious advantages of taking precise measurements in standing trees, most volume tables are still produced by less efficient methods.

One reason may be that although dendrometers and their use have been fully described, an entire measurement and recording system has not. This Paper describes the system used in forest surveys at the Southeastern Forest Experiment Station to measure standing sample trees for preparation of volume-prediction equations. This system has been refined over the past 14 years, and it should be applicable to many situations. The techniques and procedures described are not the only way to do the job, but their value has been demonstrated over a long period.

In the past 15 years many articles have been published on the different types of dendrometers available for measuring upper-stem diameters (Wheeler 1962; Grosenbaugh 1963; and McClure 1969). The reliability of these instruments has been tested in a host of studies (Nevers and Barrett 1966; Arvanitis 1968; Robbins and Young 1968; Cost 1971; and Bell and Groman 1971), but none of these studies dealt with the mensurational problems associated with measuring standing trees.

In this Paper, I (1) review mensurational problems encountered in measuring standing trees, (2) fully describe the mensurational procedures we use in the Southeast, and (3) provide the data processing equations we use to compute a variety of tree characteristics.

BACKGROUND

In 1963, midway through the third Forest Survey of North Carolina, the Forest Survey Handbook was substantially revised, and merchantability standards were changed. Cubic-foot volumes of wood in the new standards were computed to a 4.0-inch diameter outside bark rather than inside bark. For sawtimber trees, the new standards called for the board-foot volume from a 1-foot stump to a minimum top of 7.0 inches d.o.b. for softwoods and 9.0 inches d.o.b. for hardwoods. The previous standards for sawtimber had specified minimum top diameters which varied with d.b.h. To accommodate these changes, new prediction equations had to be developed from new tree-volume data.

We studied the merits of both a standing- and felled-tree sample and decided that standing-tree samples were best for most purposes. One advantage is that sample trees are not destroyed. Repeated measurements of them through time permit close estimation of growth. Another big advantage is lower cost per tree, which permits us to sample heavily in each size class with the monies available.

In 1963 we incorporated a standing-tree volume sample into the survey. Species, d.b.h. classes, and tree quality variation were well represented. The measurement procedure was designed to identify all tree components except minor limbs and tops of merchantable limbs.

To measure current utilization practices, internal cull, and upper-stem bark thickness, we have continued to measure some felled trees. Since measurements on felled trees are recorded in the same manner as those on standing trees, the data can be pooled to supplement the standing sample.

Currently, our measurements of standing trees include all branch material in the crown of all trees. Therefore, for the first time, we can determine total-tree volume. The procedures described here are quite flexible and can be applied to any species across a wide geographic range.

PURPOSE

Our standing-tree volume samples are required for several reasons. First, they provide information necessary to develop accurate volume-prediction equations by species. Second, they are used to develop length equations by species. These equations are required to predict average bole length, average saw-log length, or average total height. Third, they provide information to estimate board-foot volume by log grade and to separate cubic volume by material classes. Finally, the measured double bark thickness is used to develop equations for predicting average bark thickness at d.b.h. In the Southeast, the standing-tree volume samples are collected on a proportionate basis, so many of the derived rates, ratios, and factors collected can be extrapolated to the entire sample of permanent plots.

EQUIPMENT

In measuring upper-stem diameters, upper-stem length, and bark thickness, we use three specialized pieces of equipment:

1. *Optical dendrometer.*—All upper-stem diameters from 3 to 16 inches are measured with a 16-inch model mirror caliper. Diameters over 16 inches are measured using a special prism-series attachment. The use of the mirror caliper is described by McClure (1969).
2. *Sectional aluminum pole.*—Each section is 5 feet long and there are 24 sections in a complete set. Thus, it is possible to accurately measure heights up to 120 feet. Construction and use of these poles are described by McClure (1968).
3. *Swedish bark gage.*—Double bark thickness of each tree 3.0 inches d.b.h. or larger is measured with a bark gage. Bark measurements are used to develop regression equations, which in turn are used to convert d.o.b. measurements to d.i.b. estimates.

The measurer also needs to carry a diameter tape to measure the diameter at the 1-foot stump and d.b.h., and an increment borer and hatchet for determining the presence of cull.

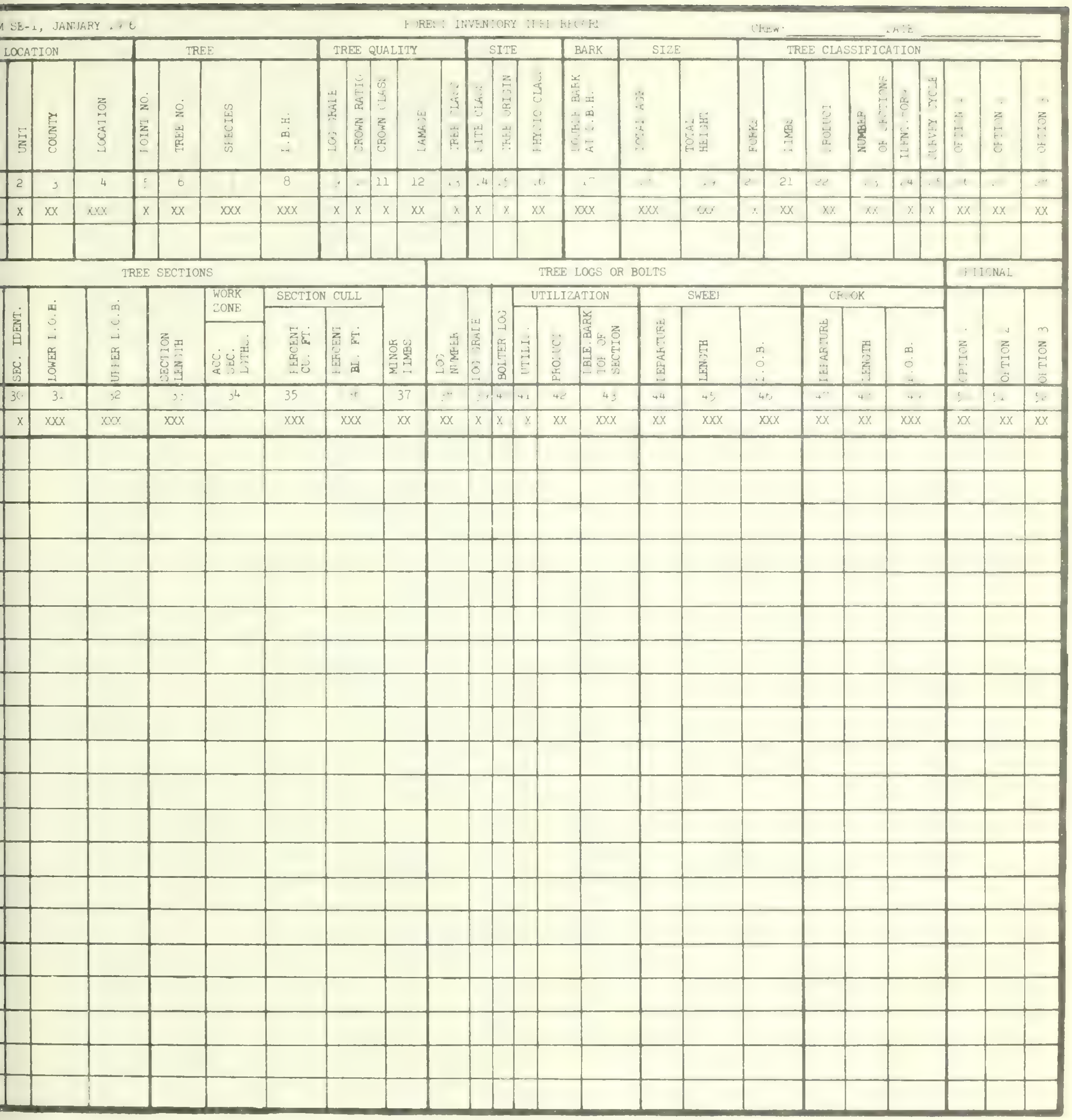
GENERAL OBSERVATIONS

After the sample tree has been identified, the marked pole is extended up through the tree crown until it protrudes slightly out the top. Prior to mentally dividing the tree into sections, the following observations should be made.

1. Identify the main stem.
2. Identify the forks.
3. Separate the major limbs and minor limbs.
4. Reconstruct missing material which has broken off.
5. Assign tentative log positions throughout the tree. Look for grade differences, jump sections, and obvious bucking points.
6. Check the tree for signs of internal rot. Rot in the lower portion can often be detected by sounding the tree with a hatchet. Internal defect in the upper portion is classified ocularly, based on surface indicators such as holes, branch stubs, bulges, and conks.
7. Finally, select the plane of the tree that faces the plot center. Repeating this procedure on each sample tree eliminates any bias that might be introduced by elliptical tree cross sections.

RECORDING TREE MEASUREMENTS

Our tally sheet (fig. 1) is designed to facilitate field entries as well as editing, punching, and processing of the data. A separate tally sheet is prepared for each tree 1.0 inch d.b.h. or larger. Our standard code for each entry on the tally sheet is described below. Other codes would probably be needed for other applications. Whatever the application, each item on the tally sheet must be precisely defined to assure standardized entries.



M SE-1, JANUARY 1976

FOREST INVENTORY TREE RECORD

CREW: ______________ DATE ______________

LOCATION			TREE				TREE QUALITY					SITE			BARK	SIZE		TREE CLASSIFICATION								
UNIT	COUNTY	LOCATION	POINT NO.	TREE NO.	SPECIES	D.B.H.	LOG GRADE	CROWN RATIO	CROWN CLASS	DAMAGE	TREE CLASS	SITE CLASS	TREE ORIGIN	PHYSIO CLASS	DOUBLE BARK AT D.B.H.	TOTAL AGE	TOTAL HEIGHT	FORKS	LIMBS	PRODUCT	NUMBER OF SECTIONS	IDENT. FOR.	SURVEY CYCLE	OPTION 1	OPTION 2	OPTION 3
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
X	XX	XXX	X	XX	XXX	XXX	X	X	X	XX	X	X	X	XX	XXX	XXX	XXX	X	XX	XX	XX	X	X	XX	XX	XX

TREE SECTIONS								TREE LOGS OR BOLTS												OPTIONAL		
				WORK ZONE	SECTION CULL						UTILIZATION			SWEEP			CROOK					
SEC. IDENT.	LOWER D.O.B.	UPPER D.O.B.	SECTION LENGTH	ACC. SEC. LNTHS.	PERCENT CU. FT.	PERCENT BD. FT.	MINOR LIMBS	LOG NUMBER	LOG GRADE	BOLTER LOG	UTILIZ.	PRODUCT	DOUBLE BARK TOP OF SECTION	DEPARTURE	LENGTH	D.O.B.	DEPARTURE	LENGTH	D.O.B.	OPTION 1	OPTION 2	OPTION 3
30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
X	XXX	XXX	XXX		XXX	XXX	XX	XX	X	X	X	XX	XXX	XX	XXX	XXX	XX	XX	XXX	XX	XX	XX

Figure 1.—Coding sheet Form SE-1.

State (Item 1).—A 2-digit code to identify the State.

Unit (Item 2).—A 1-digit code to identify the survey unit, which for us is the primary subdivision of the State. Management units might be listed in smaller operations.

County (Item 3).—A 2-digit code to identify the county within the State. In smaller applications, a stand number might be entered.

Location (Item 4).—A 3-digit code beginning with 001 in each county to identify separate series of sample location numbers within each county.

Point number (Item 5).—Since a 10-point cluster is the standard plot design used in our forest surveys, one digit is used to identify the point number within the sample location.

Tree number (Item 6).—A 2-digit code beginning with 01 for each point, to identify individual trees on a point.

Species (Item 7).—A 3-digit code to identify the species of the tree being measured. (Species codes are listed in fig. 2.)

D.B.H. (Item 8).—Three digits to identify the diameter to the nearest one-tenth inch of the tree at breast height (4½ feet above the ground). If an irregularity such as a bump or swell occurs at breast height, the diameter is measured immediately above irregularity at the point where the stem is normal. Swell-butted trees such as cypress or tupelo are measured at a point 1.5 feet above the end of the pronounced swell or bottleneck if the bottleneck is more than 3 feet high. A tree that forks below breast height is considered as two trees, and diameter is measured at a point 3½ feet above the point where the two piths intersect. When the stem forks immediately above breast height, diameter is measured below the swell at the point where the stem is normal.

Log grade (Item 9).—A 1-digit code to identify the grade of the first saw log in each sawtimber-size tree. (Grade rules are shown in fig. 2.)

Crown ratio (Item 10).—A 1-digit item that reflects the proportion of total-tree height that supports green, live foliage that contributes to the tree's growth.

Crown class (Item 11).—A 1-digit code to identify the position of the crown in the stand.

Damage (Item 12).—A 2-digit code to identify the presence of any damage or pathogen activity in the tree.

Tree class (Item 13).—A 1-digit code to identify the suitability of trees. The common tree class terms are growing stock or rough and rotten.

Site class (Item 14).—A 1-digit code that denotes the tree-growing potential for the site on which the dendrometered tree subsists.

Tree origin (Item 15).—A 1-digit code to identify if the tree has been planted or established by natural process.

Physiographic class (Item 16).—A 2-digit code to identify the physiographic condition of the area on which the tree subsists. The factors considered include topography, aspect, soil moisture, and drainage.

Double bark at d.b.h. (Item 17).—Double bark thickness at breast height. One bark thickness is taken on the side facing plot center and the other on the opposite side of the tree. The two measurements are added together and recorded to the nearest 0.01 inch. All trees 1.0 inch d.b.h. or larger are measured for double bark. A Swedish bark gage is used to measure bark on all trees 3.0 inches and larger. For trees less than 3.0 inches, a small notch is made and the bark is measured with a finely graduated scale.

Total age (Item 18).—Age of tree being dendrometered.

Total height (Item 19).—Total length (to the nearest foot) from ground level to the tip of the main stem, measured along the main stem.

Forks (Item 20).—A 1-digit code to identify the number of forks that intersect with the main stem between breast height and the 4.0-inch outside diameter (o.b.).

Limbs (Item 21).—Sum of diameters (to the nearest inch) of severe limbs on the main stem and on all forks between breast height and 4.0 inches (o.b.). This value is intended to account for the siphoning effect from merchantable bole volume. If total aboveground tree volume is the objective, the lengths and diameters of all limbs take precedence over this item.

Three guidelines for the identification of a severe limb are:

1. For hardwood species a severe limb's diameter will normally be greater than one-tenth the diameter of the stem on which it occurs.
2. A limb is considered severe if stem diameter decreases markedly immediately above the limb.
3. A severe reduction in stem diameter that requires two dendrometer readings close to each other is normally the result of a severe limb or fork intercept.

Product (Item 22).—A 2-digit code for use in felled-tree utilization studies.

Number of sections (Item 23).—A 2-digit code to identify the number of sections recorded for the entire tree. Leave this space blank until the entire tree has been measured.

Ident. 8 or 9 (Item 24).—A 1-digit code to indicate the method of measurement.

Survey cycle (Item 25).—A 1-digit code to identify the survey cycle (first, second, third, etc.) in which the tree was measured.

Options 1, 2 & 3 (Items 26-28).—Three undefined 2-digit codes for optional items.

Section number (Item 29).—A 2-digit code that is prerecorded on the tally sheet. No sections can be omitted which would cause a break in sequence. This sequence is used as a control feature in editing, computing, and accounting.

CODE	COMMON NAME
	YELLOW PINES
131	Loblolly pine
121	Longleaf pine
126	Pitch pine
128	Pond pine
107	Sand pine
110	Shortleaf pine
111	Slash pine
115	Spruce pine
123	Table-Mt. pine
132	Virginia pine
	OTHER SOFTWOODS
043	Atlantic white-cedar
221	Baldcypress
010	Fir
260	Hemlock
241	Northern white-cedar
222	Pondcypress
060	Redcedar
090	Spruce
129	White pine
	SOFT HARDWOODS
950	Basswood
762	Black cherry
694	Blackgum (lowland)
693	Blackgum (upland)
313	Boxelder
330	Buckeye
601	Butternut
740	Cottonwood
651	Cucumbertree
970	Elm
460	Hackberry
555	Loblolly-bay
652	Magnolia
316	Red maple
580	Silverbell (in mts.)
317	Silver maple
653	Sweetbay
611	Sweetgum
731	Sycamore
691	Water tupelo
920	Willow
621	Yellow-poplar
	HARD HARDWOODS
540	Ash
531	Beech
370	Birch (except yellow)
901	Black locust
837	Black oak
602	Black walnut
823	Bur oak
813	Cherrybark oak
832	Chestnut oak
826	Chinkapin oak
491	Dogwood
311	Florida maple
400	Hickory
591	Holly
552	Honeylocust
820	Laurel oak
838	Live oak
680	Mulberry
822	Overcup oak
521	Persimmon (forest grown)
830	Pin oak
835	Post oak
833	Northern red oak
806	Scarlet oak
817	Shingle oak
834	Shumard oak
812	Southern red oak
318	Sugar maple
825	Swamp chestnut oak
804	Swamp white oak
827	Water oak
802	White oak
831	Willow oak
371	Yellow birch
	MISCELLANEOUS
816	Bear oak
824	Blackjack oak
807	Bluejack oak
841	Dwarf live oak
840	Dwarf post oak
819	Turkey oak
899	Other scrub oaks
341	Ailanthus
548	American mt. ash
391	Blue beech
451	Catalpa
310	Chalk maple
421	Chestnut
661	Chinaberry
660	Domestic fruit (apple, etc.)
760	Fire cherry
701	Eastern hophornbeam
319	Mountain maple
692	Ogeechee gum
641	Osage-orange
521	Persimmon (field grown)
722	Planertree (water elm)
721	Redbay
471	Redbud
712	Royal paulownia
931	Sassafras
352	Serviceberry
581	Silverbell (except mts.)
711	Sourwood
315	Striped maple
999	Other miscellaneous trees

PHYSIOGRAPHIC CLASS

11	High mountain tops and slopes
12	Sand dunes and sand ridges
13	Low mountain tops and dry slopes
14	Sand hills
15	Mountain foothills
10	Other xeric
21	Flatwoods and dry pocosins
22	Rolling uplands
23	Bluffs
24	Mountain saddles and moist slopes
25	Natural stream levees
26	Valley bottoms
27	Mountain coves
28	Narrow stream margins
29	Broad stream margins
20	Other mesic
31	Deep swamps
32	Cypress strands
33	Small drains
34	Cypress ponds
35	Willow heads and strands
36	Bays and wet pocosins
37	Marl flats and forest prairies
30	Other hydric

SECTION IDENT.

0	Stump section
1	Saw log section, main stem
2	Upper stem section, main stem
3	Top section, main stem
4	Saw log section, fork
5	Upper stem section fork
6	Top section, fork
7	Major limb
8	Top section, major limb
9	Minor limb

CROWN CLASS

1	Open grown
2	Dominant
3	Codominant
4	Intermediate
5	Overtopped

CROWN RATIO
(percent of live crown)

1	0-9
2	10-19
3	20-29
4	30-39
5	40-49
6	50-59
7	60-69
8	70-79
9	80-89
0	90-99

DAMAGE CODES

00	No damage	
10	Insects	
20	Other disease	
21	Fusiform rust	
22	Annosus root rot	
23	Littleleaf disease	
24	Blister rust	
25	Hardwood cankers	
26	Branch stubs	5% cull
27	Top breakage	
28	Other basal defects	
30	Fire	
40	Animal	
50	Weather	
60	Suppression and stagnation	
80	Logging and related	
84	Turpentining	
90	Form (damaging)	
	Saplings only	
91	Form (culling)	
92	Off site (damaging)	
93	Off site (culling)	

TREE CLASS

1	Desirable tree
2	Acceptable tree
3	Rough tree
4	Rotten tree

TREE ORIGIN

0	Natural
1	Planted

SITE CLASS
POTENTIAL YIELD, MEAN ANNUAL INCREMENT

1	More than [illegible] cubic feet per acre
2	[illegible] cubic feet per acre
3	[illegible] cubic feet per acre
4	[illegible] cubic feet per acre
5	Less than [illegible] cubic feet per acre

Figure 2.—Coding summary for Form SE-1.

LOG GRADES FOR HARDWOOD FACTORY LUMBER LOGS (Third best face in butt log

Scaling diameter of log

Log length	8	9	10		11		12			13			14			15			16			18			20			22			24			26+		
Log grade	3	3	2	3	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
8 ft logs																																				
Clear cuttings:							Only ash, basswood																													
Min length	2	2	–	2		2		3	2	–	3	2	–	3	2	–	3	2	–	3	2	–	3	2	–	3	2		3	2	–	3	2	–	3	2
Max number	4	4		4	–	4		2	4	–	2	4	–	2	4	–	2	4	–	2	4	–	2	4	–	2	4	–	2	4	–	2	4	–	2	4
Min total length	4	4	–	4		4		6	4	–	5	4		5	4		5	4		5	4		5	4		5	4		5	4	–	5	4		5	4
Max sweep, inches	2	2	–	2		3		3	3	–	3	3	–	3	3		4	4		4	4		4	4	–	5	5	–	5	5		6	6	–	1/4D	1/4D
Max. crook, inches	3	3	–	3		4		4	4		4	4		5	5		5	5	–	5	5	–	6	6		7	7	–	7	7	–	8	8	–	1/3D	1/3D
Max. total cull, bd ft	8	11	–	14		18		22	22		26	26	–	31	31		36	36	–	42	42	–	54	54		68	68		84	84	–	101	101	–	50%	50%
10 ft logs																																				
Clear cuttings:																																				
Min. length	2	2	8	2	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2	8	3	2
Max. number	5	5	1	5	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5
Min. total length	5	5	8	5	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5	8	7	5
Max. sweep, inches	2	3	3	3	3	3	2	4	4	2	4	4	2	4	4	2	5	5	3	5	5	3	6	6	3	6	6	4	7	7	4	7	7	1/6D	.3D	1/3D
Max. crook, inches	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	8	8	8	1/3D	1/3D	1/3D
Max. total cull, bd.-ft.	11	14	18	18	23	23	23	28	28	27	34	34	32	40	40	37	46	46	43	54	54	56	69	69	70	87	87	86	107	107	103	128	128	40%	50%	50%
12 ft logs																																				
Clear cuttings:							Ash																													
Min. length	2	2	10	2	3	2	10	3	2	10	3	2	10	3	2	10	3	2	5	3	2	5	3	2	3	3	2	3	3	2	3	3	2	3	3	2
Max. number	6	6	1	6	2	6	1	3	6	1	3	6	1	3	6	1	3	6	2	3	6	2	3	6	2	3	6	2	3	6	2	3	6	2	3	6
Min. total length	6	6	10	6	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6	10	8	6
Max. sweep, inches	3	3	4	4	4	4	3	4	4	3	5	5	4	5	5	4	6	6	4	6	6	4	7	7	4	7	7	5	8	8	5	9	9	.2D	.4D	.4D
Max. crook, inches	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	8	8	8	1/3D	1/3D	1/3D
Max. total cull, bd.-ft.	13	18	23	23	28	28	28	34	34	33	41	41	39	49	49	46	57	57	52	65	65	68	84	84	85	106	106	104	129	129	124	155	155	40%	50%	50%
14 ft logs																																				
Clear cuttings:							Ash																													
Min. length	2	2	7	2	3	2	7	3	2	7	3	2	7	3	2	7	3	2	5	3	2	5	3	2	3	3	2	3	3	2	3	3	2	3	3	2
Max. number	7	7	2	7	2	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7	2	3	7
Min. total length	7	7	12	7	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7	12	9	7
Max. sweep, inches	3	4	4	4	5	5	4	5	5	4	6	6	4	6	6	4	6	7	4	7	7	4	7	8	5	8	9	5	8	10	5	9	10	.2D	.4D	.4D
Max. crook, inches	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	8	8	8	1/3D	1/3D	1/3D
Max. total cull, bd.-ft.	16	21	27	27	34	34	33	41	41	40	49	49	47	58	58	54	67	67	62	78	78	80	100	100	100	125	125	122	153	153	147	184	184	40%	50%	50%

(continued).

Figure 2. Coding summary for Form SE-1 (continued).

LOG GRADES FOR HARDWOOD FACTORY LUMBER LOGS (Third-best face in butt log) (continued)

Log length	*Scaling diamter of log*																																		
	8	9	10		11		12			13			14			15			16			18			20			22			24			26+		
Log grade	3	3	2	3	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
16-ft. logs																																				
Clear cuttings:							Ash																													
Min. length	2	2	7	2	3	2	7	3	2	7	3	2	7	3	2	7	3	2	5	3	2	5	3	2	3	3	2	3	3	2	3	3	2	3	3	2
Max. number	8	8	2	8	2	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8	2	3	8
Min. total length	8	8	13	8	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8	13	11	8
Max. sweep, inches	4	4	5	5	5	5	4	6	6	4	6	6	4	6	7	4	6	7	4	7	8	5	7	9	5	8	10	5	9	11	6	9	12	.2D	.4D	.5D
Max. crook, inches	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	8	8	8	1/3D	1/3D	1/3D
Max. total cull, bd.-ft.	19	25	32	32	40	40	39	48	48	46	57	57	54	68	68	63	78	78	72	90	90	93	116	116	116	145	145	142	177	177	170	212	212	40%	50%	50%
18-ft. logs							Ash																													
Clear cuttings:																																				
Min. length	2	2	7	2	3	2	7	3	2	7	3	2	7	3	2	7	3	2	5	3	2	5	3	2	3	3	2	3	3	2	3	3	2	3	3	2
Max. number	9	9	2	9	2	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9	2	3	9
Min. total length	9	9	15	9	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9	15	12	9
Max. sweep, inches	4	5	5	6	6	6	4	6	7	4	6	7	4	6	8	4	7	8	5	7	9	5	8	10	5	8	11	6	9	12	6	9	13	.2D	.4D	.6D
Max. crook, inches	3	3	3	3	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	6	6	6	7	7	7	7	7	7	8	8	8	1/3D	1/3D	1/3D
Max. total cull, bd. ft.	22	30	37	37	47	47	44	55	55	54	67	67	62	77	77	72	90	90	82	102	102	106	132	132	132	165	165	162	202	202	194	242	242	40%	50%	50%

SOUTHERN PINE GRADES

For softwoods, always grade the bottom 16-foot log, or the first merchantable log 12 feet or longer in the tree.

Face = 1/4 the circumference of the log

Clear Face = Free of knots measuring more than 1/2 inch in diameter, overgrown knots of any size, holes more than 1/4 inch in diameter. The faces may be rotated if necessary to obtain the maximum number of clear ones.

Overgrown Knot = A knot overgrown and buried beneath the log surface, but indicated by a surface bump or disturbance of bark pattern.

Tentative Grades

Grade 1.—Logs with 3 or 4 clear faces

Grade 2.—Logs with 1 or 2 clear faces.

Grade 3. Logs with no clear faces

Degrade for Sweep or Heart Rot

a. Degrade any tentative 1 or 2 log one grade if sweep amounts to 3 or more inches and equals or exceeds one third (1/3) the diameter inside bark at small end. This is the final grade if there is no evidence of heart rot.

b Degrade any tentative 1 or 2 log one grade if conk, massed hyphae, or other evidence of advanced heart rot is found anywhere in it.

HARDWOOD TIE AND TIMBER GRADE

(Examine entire log)

Scaling diameter.—8-inch minimum

Log length.—8-foot minimum

Knots or limbs

Single knot or limb does not exceed 1/3 stem diameter at point of occurrence.

Grouped knots or limbs.—Sum of diameters in any 6-inch stem section does not exceed 1/3 stem diameter at point of occurrence.

Maximum sweep allowed (inches departure)

Log length	Maximum sweep by log scaling diam									
	8	10	12	14	16	18	20	22	24	26+
8	2	2	3	3	4	4	5	5	6	1/4D
10	2	3	4	4	5	6	6	7	7	1/3D
12	3	4	4	5	6	7	7	8	9	.4D
14	3	4	5	6	7	8	9	10	10	.4D
16	4	5	6	7	8	9	10	11	12	.5D
18	4	6	7	8	9	10	11	12	13	.6D

Maximum crook allowed. Departure in inches not to exceed 1/3 diameter of log segment at point of occurrence.

Internal rot.—None allowed.

Total cull.—Not over 50% of gross board-foot volume.

Figure 2 - Coding summary for Form SE-1 *(continued).*

Section identification (Item 30).—A 1-digit code to identify the type of material represented by the section's measurements. Ten identity codes represent the portions of the entire tree from ground to the tip (fig 3):

Main stem codes

- Code 0 — Stump material.
- Code 1 — Softwood material 7.0+ inches or hardwood material 9.0+ inches.
- Code 2 — Softwood material 7.0 inches to 4.0 inches, or hardwood material 9.0 inches to 4.0 inches.
- Code 3 — Softwood or hardwood material 4.0 inches to 0.0 inch.

Fork codes

- Code 4 — Softwood material 7.0+ inches or hardwood material 9.0+ inches.
- Code 5 — Softwood material 7.0 inches to 4.0 inches, or hardwood material 9.0 to 4.0 inches.
- Code 6 — Softwood or hardwood material 4.0 inches to 0.0 inch.

Major limb codes

- Code 7 — Softwood or hardwood material 4.0 inches or larger at the limb base and 4.0 inches at the small end.
- Code 8 — Softwood or hardwood material 4.0 inches to 0.0 inch.

Minor limb code

- Code 9 — Softwood or hardwood limb 0.5 inch to 4.0 inches at the limb base, that occurs on the main stem, forks, and major limbs, to the tip.

The separation of limbs and forks in some hardwood species is sometimes difficult. The general rules for making this separation are:

1. The diameter of a limb is normally less than half the diameter of the main stem, at the point of branching.
2. A limb will usually occur at an angle of from 45° to 90° in relation to the main stem.
3. Limbs often occur in multiples at the point of branching. Forks generally result in two stems.
4. The first major branching from the main stem is usually a fork. Subsequent branching further up the stem will tend to be limbs.
5. A limb will not ordinarily have the potential of containing a merchantable saw log.

Lower diameter outside bark (Item 31).—The lower diameter of each section measured in the tree. Measurement of tree diameters starts at the ground. The stump section (No. 01) will have a groundline and upper d.o.b. greater than the tree's d.b.h. The lower d.o.b. for sections 02, 03, etc., will be equal to or less than the upper d.o.b. of the previous section unless a new fork or limb is started. All lower d.o.b. measurements must be equal to or greater than the upper d.o.b. of the same section.

No d.o.b. measurements are taken at points of abnormal swell or within limb or fork swells. When a measurement point occurs within one of these areas, the section length is carried to the pith intercept, the upper-section lower d.o.b. is taken above the swell, and the lower-section upper d.o.b. is taken below the swell. This procedure excludes the swell material, yet accounts for the reduction in stem diameter at this point.

Stem distortion due to bark irregularities must be considered. Comparing mechanical caliper and optical caliper readings provides a basis for adjusting dendrometer readings downward. Each tree should be measured from point center or opposite point center to prevent accumulated bias from tree ellipiticalness.

The lower d.o.b. of sections identified as tops (codes 3, 6, or 8) should not be larger than 4.0 inches o.b. For sections identified as minor limbs (code 9), lower d.o.b. can represent (1) the actual d.o.b. of one minor limb, or (2) an average d.o.b. (to the nearest 1-inch class) for several minor limbs in the tree having about the same diameter at the limb base. For example, five minor limbs with diameters of 0.6, 0.9, 1.1, 1.2, and 1.4 would have an average d.o.b. of 1.0 (recorded as 010). No lower d.o.b. should be left blank or recorded as 00.0.

Upper diameter outside bark (Item 32).—A 3-digit item to identify the upper diameter of each section measured in the tree. The general rules covered in lower d.o.b. apply to upper d.o.b. with a few exceptions. The upper d.o.b. of sections identified as saw-log material (code 1 or 4) should not be less than 7.0 inches for softwoods and 9.0 inches for hardwoods. Sections identified as upper-stem material (codes 2, 5, or 7) should not be below 4.0 inches d.o.b.

In normally tapering trees, the upper d.o.b. of the section will be the lower d.o.b. of the next section, as long as forks or limbs are not encountered.

Section length (Item 33).—The length of the section being measured to the nearest 0.1 foot. A marked pole is used to measure section length. Saw-log sections should be 4.0 feet long whenever possible. Upper-stem sections should be 5.0 feet long. Top and limb sections may be any length but should be broken into more sections if severe taper is caused by limbs.

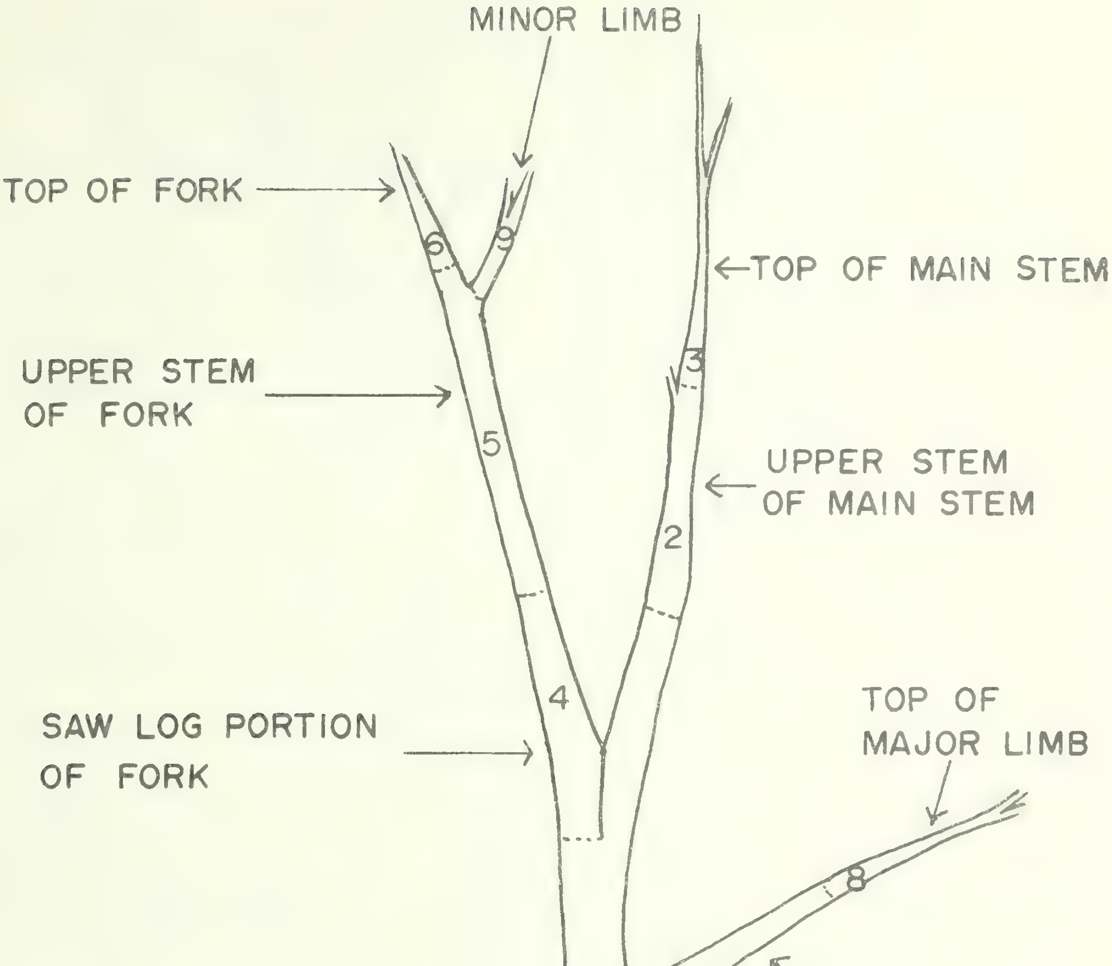


FIG. 3 - SECTION IDENTITY CODES

Figure 3.—Section identity codes.

Accumulated section lengths (Item 34).—A work space for tallyman to accumulate the total length of section codes 0, 1, 2, or 3 for sawtimber-size trees and codes 0, 2, and 3 for trees 4.0 inches d.b.h. to sawtimber-size trees. The accumulated length should agree with the total height recorded in Item 19. This item is only for field use; it is not used in computer processing.

Cubic-foot cull percentage (Item 35).—The percentage of internal cull in each section that results from rot or missing wood. Tree sections that have been turpentined are not considered cubic cull; they can be used for pulpwood, fenceposts, or fuelwood. Sweep, crook, forks, and limbs are not considered cubic-foot cull. In softwoods, no cull volume should be deducted for sound knots.

The presence of cubic cull can be determined in one of two ways, depending on where it occurs in the tree. If cull is suspected in the lower portion of the tree, it can be detected by sounding with a hatchet or by extracting a core with an increment borer. For sections out of reach, one must look for external indicators as a basis for cull determination.

For a rule of thumb, the cubic cull percentage can be computed in the following manner:

$$\begin{array}{l}\text{Cubic cull}\\ \text{percentage}\end{array} = \frac{(\text{diameter of cull portion})^2}{(\text{diameter inside bark})^2}\ (100)$$

Board-foot cull percentage (Item 36).—The percentage of board-foot cull in each saw-log section and bolter-log section resulting from rot, roughness, or other defect. These defects reduce the amount of lumber otherwise recoverable from a log. The kinds of defects considered include butt wounds, forks, large limbs, surface wounds (such as lightning scars), red heart, embedded wire or nails, and broken tops.

Three formulas, as outlined by Grosenbaugh (1952), are well suited for computing board-foot cull percentage for the defects listed. In all three formulas, d is average diameter inside bark at small end of log, and L is length of the section in feet.

1. Board-foot cull percentage when defect affects entire cross section:

$$\left(\frac{\text{Length of defect}}{L}\right)(100)$$

2. Board-foot cull percentage when defect is shaped as a wedge:

$$\left(\frac{\text{Length of defect}}{L}\right)\left(\frac{\text{Central angle of defect}}{360^\circ}\right)(100)$$

3. Board-foot cull percentage when the average cross section of interior defect is enclosable in ellipse or circle with major and minor diameter measurable in inches:

$$\left(\frac{(\text{Major})(\text{Minor})}{(d-1)^2}\right)\left(\frac{\text{Length of defect}}{L}\right)(100)$$

Minor limbs (Item 37).—A 2-digit code to identify the number of minor limbs in designated size class. Since there is a tendency for limbs to vary in size and length, it is necessary to segregate the limbs into different classes. Two broad classes of minor limbs are recognized:

1. A single limb much larger in diameter or length than other limbs on the tree.
2. Several limbs either in a bunch or scattered throughout the tree, that are about the same diameter and length.

When one minor limb is singled out to be measured, a 01 is recorded. If several limbs are averaged together, the total number of limbs is recorded for the minor limb count.

Log number (Item 38).—A 2-digit code which separates the tree into a series of material classes. Each merchantable log and bolter log within the main stem or forks of a tree is given a unique number. Each section within the log is assigned this number. In addition, each jump section, upper stem, top, stump, or limb section within the tree is assigned a separate log number (fig. 4).

Log grade (Item 39).—A 1-digit item to identify the log grade of each merchantable section in the saw-log portion of the tree. For grading purpose, each merchantable section is assembled into 8- to 16-foot logs. For hardwoods, log sections are visually squared up into four sides or faces. The face with the most defects is disregarded. Grade determination is based upon scaling diameter and number and length of clear sections without defect on the poorest of the three remaining faces. Southern pine grade is based entirely upon the number of clear faces. A face is one-fourth of the circumference in width and extends the full length of the log. All other softwood species are graded by white pine grade rules.

Bolter log (Item 40).—A 1-digit code to identify whether the section meets the requirements for a hardwood bolter log. These requirements are:

1. Length normally 4 to 8 feet and not less than 4 feet.
2. Scaling diameter of at least 7.0 inches o.b.
3. Must meet minimum requirements for a grade 3 Hardwood Factory Lumber

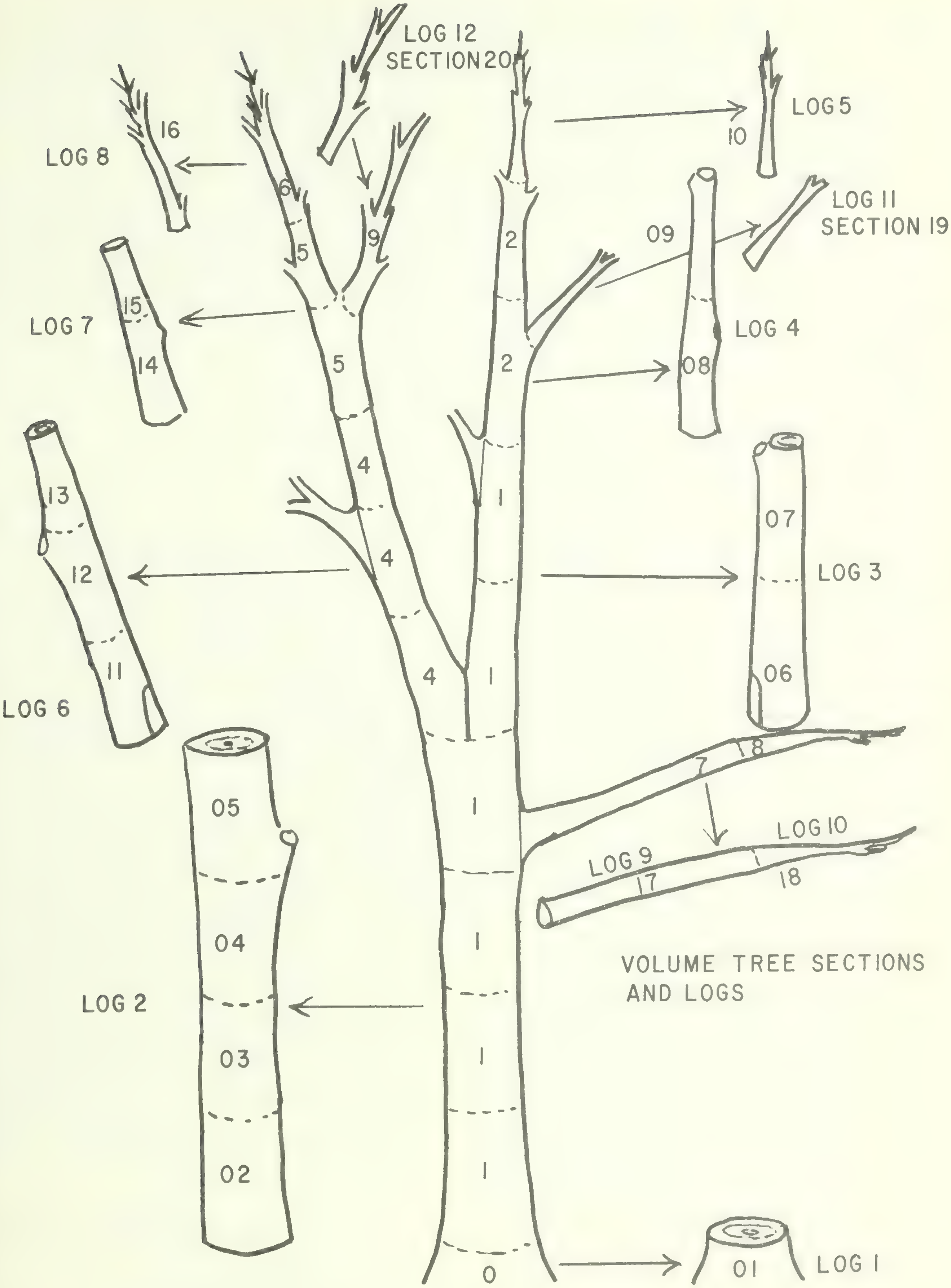


Figure 4.—Volume tree sections and log numbers.

Log (fig. 2). For logs less than 8 feet, the grade specifications are prorated, based on length.

Utilization (Item 41).—A 1-digit code for use in a felled-tree utilization study.

Product (Item 42).—A 1-digit code for use in a felled-tree utilization study.

Double bark thickness, top of section (Item 43).—A 3-digit code for use in a felled-tree utilization study.

Sweep departure (Item 44).—A 2-digit code to quantify sweep in the log. One inch or less of sweep per 8 feet of log is ignored. Sweep departure is recorded when the central axis or the portion with sweep departs more than 1 inch from an imaginary straight line that connects the centers at the ends of the log.

Sweep length (Item 45).—The length of the portion of the log with sweep to the nearest 0.1 foot. Sweep is generally 6 feet or more in length.

Sweep d.o.b. (Item 46).—Scaling diameter of the portion of the log with sweep.

Crook departure (Item 47).—A 2-digit code to identify an abrupt bend deviating from the straight longitudinal axis of the log.

Crook length (Item 48).—The length of the portion of the log with crook to the nearest 0.1 foot. Crooks are generally less than 6 feet in length.

Crook d.o.b. (Item 49).—Scaling diameter of the portion of the log with crook.

Options 1, 2 & 3 (Items 50-52).—Three 2-digit codes for optional items. If other pertinent information is needed by tree section, these items can be activated.

Figure 5 shows a tally sheet that is completed. The lower and upper d.o.b.'s for each tree section are shown in figure 6.

DATA PROCESSING

Conversion of the information collected on standing trees into volume equations requires the assistance of an electronic computer. We transfer all sample-tree data from the field forms to punched cards. These cards are run through a comprehensive editing program which identifies valid codes, omissions, incorrect measurements, and illogical section sequences or relationships between various measurements and classifications. Error listings identify the types of errors. After the initial errors are corrected, a second edit is made to ensure that new errors have not been introduced.

Next, the data are processed with a special volume computer program which computes diameters inside bark, section volumes and losses to sweep or crook, and summaries of volume by material class and quality.

Finally, for each tree, two levels of information are produced and stored on magnetic tape for future retrieval. One tape contains tree sections in full detail, while the other is a special tree summary.

BARK COEFFICIENT

If volume without bark is one of the objectives, all outside diameters must be converted to diameters inside bark (d.i.b.). Bark coefficients used to estimate d.i.b. are derived with computer-generated regression equations which predict double bark thickness as a function of diameter outside bark (d.o.b.) by species. Two bark coefficients result from each equation model:

$$Y_1 = a + b(\text{d.b.h.})$$

$$Y_2 = c + d(\text{d.o.b.})$$

where:

Y_1 = double bark thickness at 4.5 feet above ground (inches)
Y_2 = double bark thickness above 4.5 feet (inches)
a, b, c, d = regression coefficients
d.o.b. = diameter outside bark
d.b.h. = diameter at 4.5 feet

Observed values of Y_2 for computation of the regression equation are obtained from felled trees.

PROGRAMED EQUATIONS

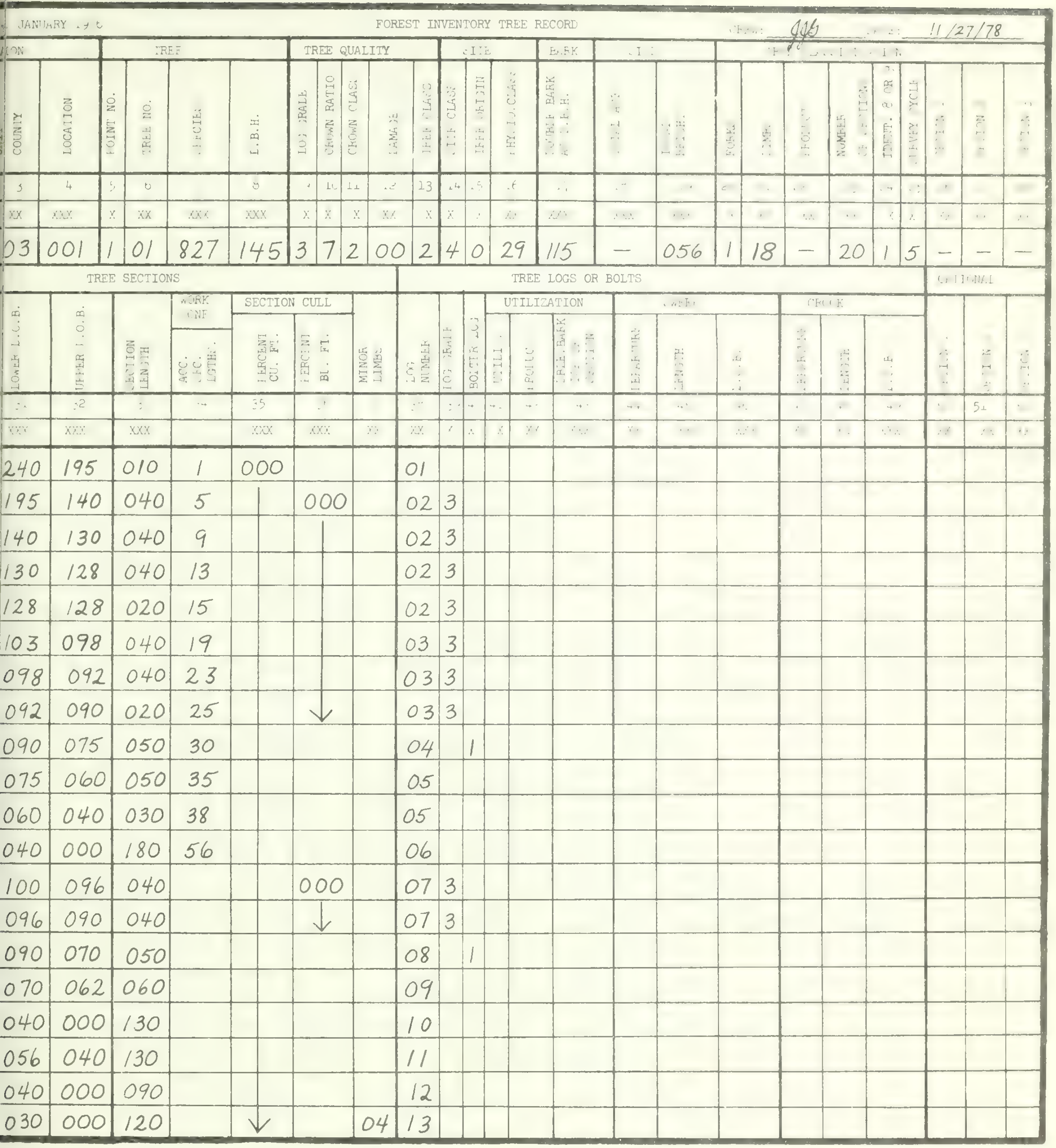
The method for estimating bark thickness at a point depends on the point's height above ground. The steps that are involved are:

1. The measured double bark thickness at breast height is used to adjust the predicted bark thickness based on the ratio difference found at breast height. This difference is expressed as a bark adjustment factor (b.a.f.).
2. For a point 7 feet in height or less, the equation for predicting double bark thickness is:

$$\text{Double bark thickness (inches)} = [a + b(\text{d.o.b.})](\text{b.a.f.})$$

3. For a point above 7 feet but less than 16 feet in height, the two equations are blended:

$$B_1 = \left[\frac{\text{Height above ground} - 7.0}{9.0}\right]\left[c + d\,(\text{d.o.b.})\right]$$



JANUARY 19[illegible] FOREST INVENTORY TREE RECORD [illegible]: JJS [illegible]: 11/27/78

ION		TREE				TREE QUALITY					SITE			BARK	[illegible]		[illegible]								
COUNTY	LOCATION	POINT NO.	TREE NO.	SPECIES	D.B.H.	LOG GRADE	CROWN RATIO	CROWN CLASS	DAMAGE	TREE CLASS	SITE CLASS	TREE ORIGIN	PHY. ID. CLASS	DOUBLE BARK AT D.B.H.	[illegible]	[illegible] HEIGHT	FOREST	[illegible]	[illegible]	NUMBER OF SECTIONS	IDENT. 8 OR 9	SURVEY CYCLE	[illegible]	[illegible]	[illegible]
3	4	5	6		8	[illegible]	10	11	12	13	14	15	16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
XX	XXX	X	XX	XXX	XXX	X	X	X	XX	X	X	X	XX	XXX	[illegible]	[illegible]	X	[illegible]	[illegible]	[illegible]	X	X	[illegible]	[illegible]	[illegible]
03	001	1	01	827	145	3	7	2	00	2	4	0	29	115	—	056	1	18	—	20	1	5	—	—	—

TREE SECTIONS							TREE LOGS OR BOLTS												ORIGINAL		
			WORK CNF	SECTION CULL						UTILIZATION			SWEEP			CROOK					
LOWER D.O.B.	UPPER D.O.B.	SECTION LENGTH	ACC. SEC. LGTHS.	PERCENT CU. FT.	PERCENT BD. FT.	MINOR LIMBS	LOG NUMBER	LOG GRADE	BOLTER LOG	UTILI.	PRODUC	FREE BARK [illegible]	DEPARTURE	LENGTH	L.O.F.	DEPARTURE	LENGTH	L.O.F.	[illegible]	[illegible]	[illegible]
[illegible]	32	[illegible]	[illegible]	35	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	51	[illegible]
XXX	XXX	XXX		XXX	XXX	XX	XX	X	X	X	XX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
240	195	010	1	000			01														
195	140	040	5		000		02	3													
140	130	040	9				02	3													
130	128	040	13				02	3													
128	128	020	15				02	3													
103	098	040	19				03	3													
098	092	040	23				03	3													
092	090	020	25		↓		03	3													
090	075	050	30				04		1												
075	060	050	35				05														
060	040	030	38				05														
040	000	180	56				06														
100	096	040			000		07	3													
096	090	040			↓		07	3													
090	070	050					08		1												
070	062	060					09														
040	000	130					10														
056	040	130					11														
040	000	090					12														
030	000	120		↓		04	13														

Figure 5.—Coding sheet Form SE-1 containing data for sample tree in figure 6.

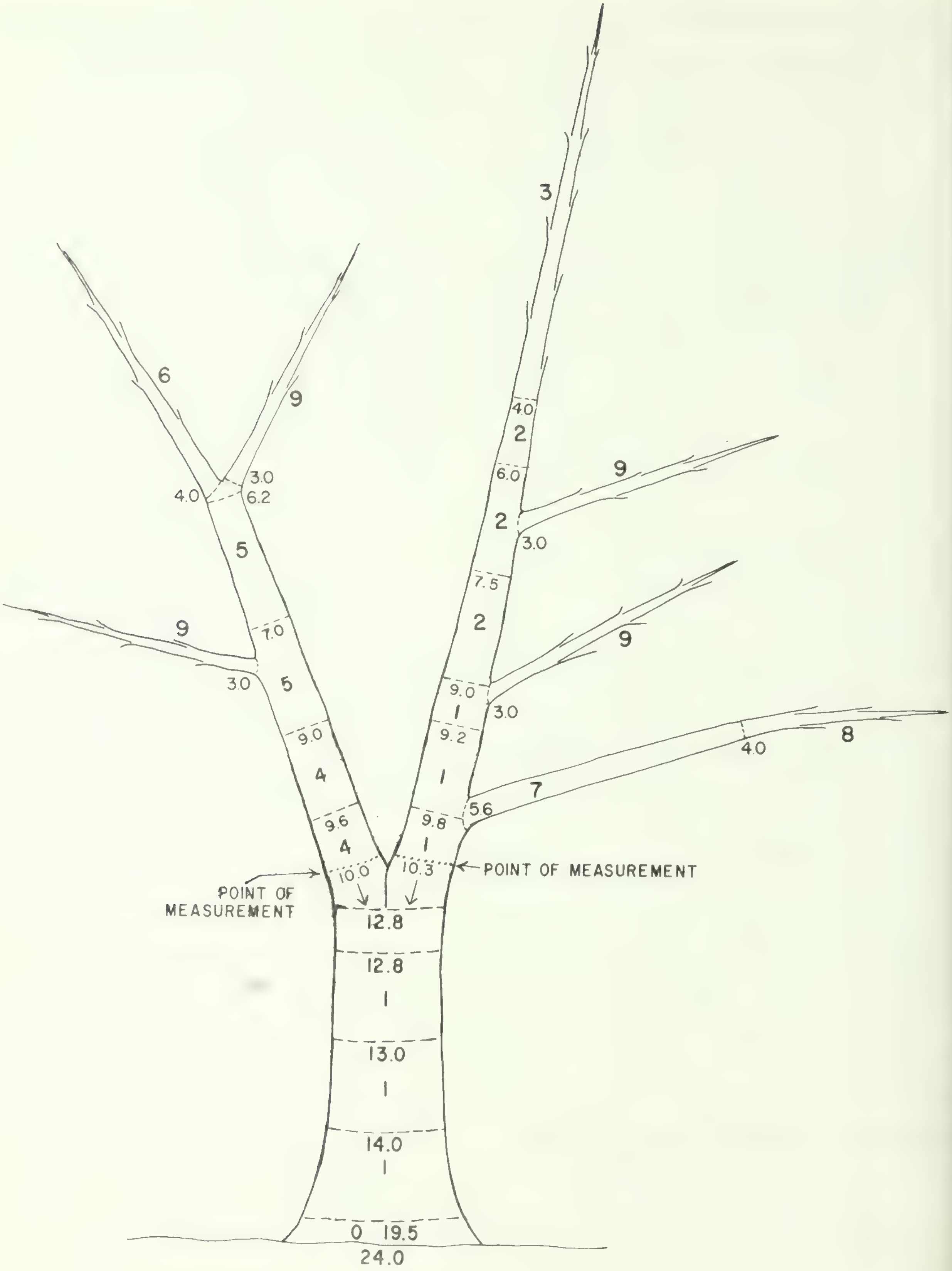


Figure 6.—Sample tree.

$$B_2 = \left[\frac{16.0 - \text{Height above ground}}{9.0}\right]\left[a + b(\text{d.o.b.})\right]$$

thus:

Blended double bark thickness (inches)

$$= [B_1 + B_2]\,(\text{b.a.f.})$$

where:

B_1, B_2 = double bark thickness (inches)

4. The bark thickness equation for a point above 16 feet is:

Double bark thickness (inches)

$$= [c + d\,(\text{d.o.b.})]\,(\text{b.a.f.})$$

The other programed equations are Grosenbaugh's (1952) formulas for cubic- and board-foot volume (International ¼-Inch Log Rule):

$$\text{Volume } (\text{ft}^3) = 0.005454154\ L\left[Dd + \frac{(D-d)^2}{K}\right]$$

where:

L = section length (feet)
D = diameter inside bark, large end (inches)
d = diameter inside bark, small end (inches)
K = constant (varies by section identity)

Section identity	*K value*
0	4
1, 2, 4, 5, or 7	3
3, 6, 8, or 9	2.45

$$\begin{aligned}\text{Volume (fbm)} =\ & 0.04976191\,(Ld^2) + 0.006220239\,(L^2 d)\\ & -0.1854762\,(Ld) + 0.0002591767\,(L^3)\\ & -0.01159226\,(L^2) + 0.04222222\,(L)\end{aligned}$$

To compute a net board-foot volume, the defective portion must be deducted from the gross volume. Two formulas are used to calculate the loss due to sweep and crook:

Volume (fbm) (sweep loss)

$$= \left[\frac{(\text{Departure} - \text{Sweep length}/8.0)}{\text{affected section d}}\right] X$$

[affected section gross fbm volume]

Volume (fbm) (crook loss)

$$= \left[\frac{\text{Departure}}{\text{affected section d}}\right] X$$

[affected section gross fbm volume]

OUTPUT DATA

The processing system stores the tree information on magnetic tape. The data on magnetic tape are stored at two levels.

The first level is very detailed. It contains all the basic tree measurements and computed values, by tree section.

Standing or Felled-Tree Section Tape

Fields	*Descriptions*	*Form*
1	Tree indicator	X
2–3	State	XX
4	Unit	X
5–6	County	XX
7–9	Location	XXX
10	Point number	X
11–12	Tree number	XX
13–15	Species	XXX
16–18	D.B.H.	XX.X
19	Log grade	X
20	Crown ratio	X
21	Crown class	X
22–23	Damage	XX
24	Tree class	X
25	Site class	X
26	Tree origin	X
27–28	Physiographic class	XX
29–31	Double bark at d.b.h.	X.XX
32–34	Total age	XXX
35–37	Total height	XXX
38	Number of forks	X
39–40	Sum of major limb diameters	XX
41–42	Product (felled tree only)	XX
43–44	Number of tree sections	XX
45	Ident. 8 or 9	X
46	Survey cycle	X

For each tree section there is:

1	Section indicator	X
2–3	Section number	XX
4	Section ident.	X
5–7	Lower diameter outside bark	XX.X
8–10	Lower diameter inside bark	XX.X
11–13	Upper diameter outside bark	XX.X
14–16	Upper diameter inside bark	XX.X

17-19	Section length	XX.X
20-22	Cubic cull rate	X.XX
23-25	Board-foot cull rate	X.XX
26-27	Number of minor limbs	XX
28-29	Log number	XX
30	Log grade	X
31	Bolter log	X
32	Utilization	X
33-34	Product (felled tree only)	XX
35-37	Double bark top of section (felled tree only)	X.XX
38-41	Sweep and crook loss	XXX.X
42-46	Cubic volume, including bark	XXX.XX
47-51	Cubic volume, excluding bark	XXX.XX
52-56	Net cubic volume	XXX.XX
57-61	Gross board-foot volume	XXXX.X
62-66	Net board-foot volume	XXXX.X

The second level tape that the program produces is a tree summary.

Tree Summary Tape

Fields	*Descriptions*	*Form*
1-2	State	XX
3	Unit	X
4-5	County	XX
6-8	Location	XXX
9	Point number	X
10-11	Tree number	XX
12-14	Species	XXX
15-17	D.B.H.	XX.X
18	Log grade	X
19	Crown ratio	X
20	Crown class	X
21-22	Damage	XX
23	Tree class	X
24	Site class	X
25	Tree origin	X
26-27	Physiographic class	XX
28-30	Double bark at d.b.h.	X.XX
31-33	Total age	XXX
34	Number of forks	X
35-36	Sum of major limb diameters	XX
37-38	Product (felled tree only)	XX
39-40	Number of sections	XX
41	Ident. 8 or 9	X
42	Survey cycle	X
43-44	Optional zone 1	XX
45-46	Optional zone 2	XX
47-48	Optional zone 3	XX
49-52	Merchantable length	XXX.X
53-56	Saw-log length	XXX.X
57-60	Bole length	XXX.X
61-64	Total length	XXX.X
65-67	Stump top diameter outside bark	XX.X
68-70	Merchantable top diameter outside bark	XX.X
71-73	Saw-log top diameter outside bark	XX.X
74-76	Bole-top diameter outside bark	XX.X
77-80	Cubic volume with bark for section ident. 0	XX.XX
81-85	Cubic volume with bark for section ident. 1	XXX.XX
86-89	Cubic volume with bark for section ident. 2	XX.XX
90-92	Cubic volume with bark for section ident. 3	X.XX
93-97	Cubic volume with bark for section ident. 4	XXX.XX
98-101	Cubic volume with bark for section ident. 5	XX.XX
102-104	Cubic volume with bark for section ident. 6	X.XX
105-108	Cubic volume with bark for section ident. 7	XX.XX
109-112	Cubic volume with bark for section ident. 8	XX.XX
113-116	Cubic volume with bark for section ident. 9	XX.XX
117-120	Cubic volume without bark for section ident. 0	XX.XX
121-125	Cubic volume without bark for section ident. 1	XXX.XX
126-129	Cubic volume without bark for section ident. 2	XX.XX
130-132	Cubic volume without bark for section ident. 3	X.XX
133-137	Cubic volume without bark for section ident. 4	XXX.XX
138-141	Cubic volume without bark for section ident. 5	XX.XX
142-144	Cubic volume without bark for section ident. 6	X.XX
145-148	Cubic volume without bark for section ident. 7	XX.XX
149-152	Cubic volume without bark for section ident. 8	XX.XX
153-156	Cubic volume without bark for section ident. 9	XX.XX
157-160	Net cubic volume for section ident. 0	XX.XX
161-165	Net cubic volume for section ident. 1	XXX.XX
166-169	Net cubic volume for section ident. 2	XX.XX

170-172	Net cubic volume for section ident. 3	X.XX
173-177	Net cubic volume for section ident. 4	XXX.XX
178-181	Net cubic volume for section ident. 5	XX.XX
182-184	Net cubic volume for section ident. 6	X.XX
185-188	Net cubic volume for section ident. 7	XX.XX
189-192	Net cubic volume for section ident. 8	XX.XX
193-196	Net cubic volume for section ident. 9	XX.XX
197-201	Gross board-foot volume for section ident. 4	XXXX.X
202-206	Gross board-foot volume for section ident. 1	XXXX.X
207-211	Net board-foot volume for section ident. 4	XXXX.X
212-216	Net board-foot volume for section ident. 1	XXXX.X
217-219	Board-foot cull volume due to internal rot	XXX
220-222	Board-foot cull volume due to jump sections	XXX
223-225	Board-foot cull volume due to sweep and crook	XXX
226-229	Net board-foot volume of grade 1	XXXX
230-233	Net board-foot volume of grade 2	XXXX
234-237	Net board-foot volume of grade 3	XXXX
238-241	Net board-foot volume of grade 4	XXXX
242-246	Net board-foot volume of bolter logs	XXXX.X
247-249	1st upper-stem bark (d.o.b.)	XX.X
250-252	1st upper-stem double bark thickness	X.XX
253-255	2d upper-stem bark (d.o.b.)	XX.X
256-258	2d upper-stem double bark thickness	X.XX
259-261	3d upper-stem bark (d.o.b.)	XX.X
262-264	3d upper-stem double bark thickness	X.XX
265-267	4th upper-stem bark (d.o.b.)	XX.X
268-270	4th upper-stem double bark thickness	X.XX
271-273	5th upper-stem bark (d.o.b.)	XX.X
274-276	5th upper-stem double bark thickness	X.XX
277-281	Net cubic volume in merchantable sections	XXX.XX
282-285	Net cubic volume in upper stem	XX.XX

APPLICATIONS

The primary advantage of this system is that it will work on both standing and felled trees. The system is recommended for: (1) building volume tables, volume equations, and length equations; (2) determining timber sales volume; (3) studying taper rates, limb occurrence, and limb severity; (4) remeasuring trees over a period of time; (5) checking existing volume tables for applicability; (6) building yield tables; (7) checking the length estimating ability of individual cruisers.

Since the identities of all aboveground components of a tree are retained, other uses are possible:

1. Determining the additional yield of fiber that could be expected from stump, crown, limbs, and bark of trees.
2. Relating sizes of tree components to treatments like fertilizer application.
3. Predicting amounts of logging residue by size of material.

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Procedures for measuring standing trees in forest surveys in the Southeast are described. Field tally sheets and data processing equations are provided.

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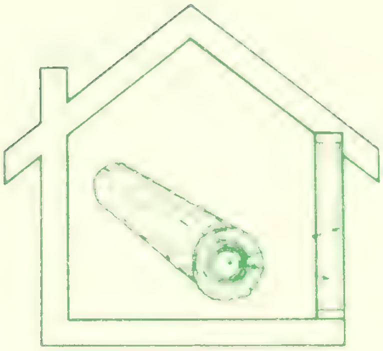

COM-PLY® REPORT 15

ECONOMIC FEASIBILITY OF MANUFACTURING COM-PLY STUDS IN THE SOUTH

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

NATIONAL FOREST SYSTEM · COOPERATIVE FORESTRY · FORESTRY RESEARCH

COOPERATIVE RESEARCH

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November 1978

Southeastern Forest Experiment Station
Asheville North Carolina

ECONOMIC FEASIBILITY OF MANUFACTURING COM-PLY STUDS IN THE SOUTH

by

Gerald A. Koenigshof, Principal Wood Scientist
Forestry Sciences Laboratory
Athens, Georgia

Cooperative Research by
U.S. Department of Agriculture, Forest Service
Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development
Division of Energy, Building Technology
and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing was initially limited to COM-PLY studs but has now been extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The Forest Service of the U.S. Department of Agriculture and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of COM-PLY studs and joists is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall and floor framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs and joists. Other reports will describe the overall project, compare the strength of composite and solid wood lumber, suggest performance standards for composite lumber and provide construction details on houses incorporating such lumber. Still others will explore the economic feasibility of manufacturing composite lumber and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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ECONOMIC FEASIBILITY OF MANUFACTURING COM-PLY STUDS IN THE SOUTH

Abstract.--The investment and production cost required to manufacture COM-PLY studs in the South are presented. It is possible to obtain a 20 percent or greater internal rate of return on an investment in manufacturing COM-PLY studs.

KEYWORDS: Manufacturing costs, stud cost, economics of stud manufacture, cost analysis, COM-PLY factory, rate of return.

Cooperative research by the Forest Service, U.S. Department of Agriculture, and the U.S. Department of Housing and Urban Development has led to development of a new composite lumber product. The new product, called COM-PLY, has potential for significantly increasing our supply of lumber for building homes. COM-PLY lumber is a structural sandwich construction with a particleboard core between layers of solid wood veneer.

The first composite lumber product developed was a 2 x 4 wall stud typically used to frame exterior walls in houses (fig. 1). COM-PLY studs are intended to be used as direct substitutes for conventional studs of sawn lumber and must be priced competitively.

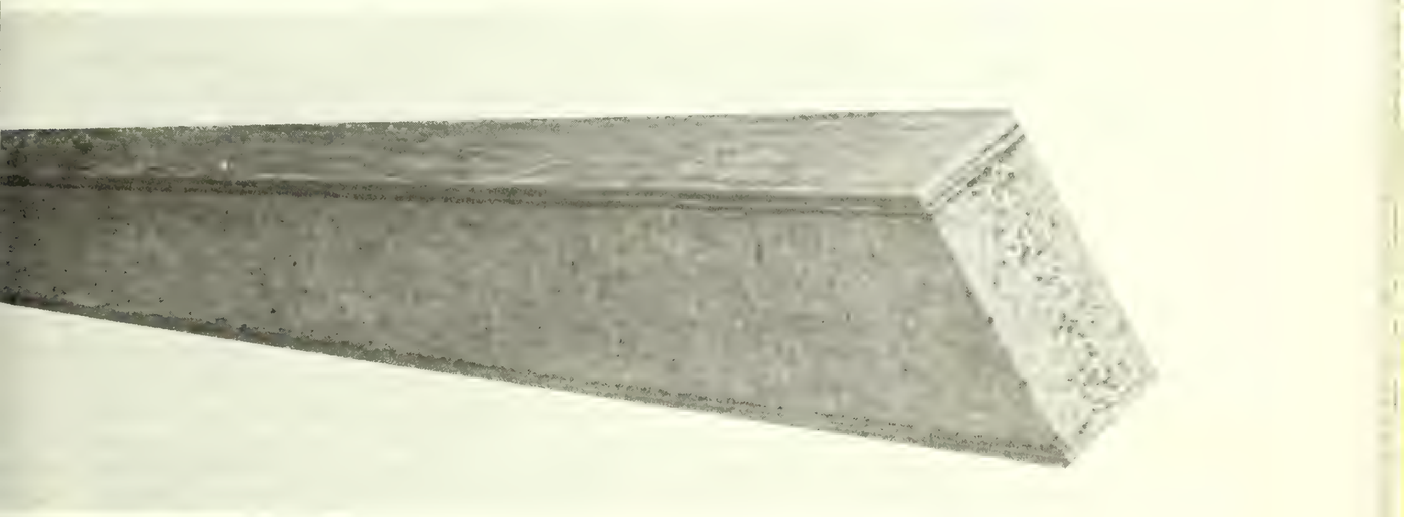

Figure 1.--COM-PLY stud used for framing exterior walls of houses.

Potential manufacturers of COM-PLY studs want to know how much it will cost to make them. They also want to know if a COM-PLY stud factory would be a profitable investment, one that would give a greater return on the investment than a sawmill. This report presents estimates on the amount of investment required to build a COM-PLY stud factory; the cost of manufacturing COM-PLY studs; the annual sales and operating cash flows; and the annual net cash flows and internal rate of return.

A study of financial feasibility is only as good as the validity of the assumptions upon which it is based. In this study, we assume that the factory is located in Arkansas and uses both hardwood and southern pine for its wood supply. The assumptions concerning costs are based on industry averages and therefore do not reflect values for any specific company.

Results presented in this report are no guarantee that any firm can profitably manufacture COM-PLY studs--profitability depends on competent managerial skills, market demand, production efficiency, and other business factors. However, the results strongly indicate that it is economically feasible to manufacture COM-PLY studs. Although a specific firm's assumptions about price, cost, and quantity may vary from those in this report, minor variances would not greatly affect the overall conclusions reported.

FINANCIAL FEASIBILITY ANALYSIS

PROCESS USED FOR MANUFACTURE

The results of any analysis of financial feasibility are greatly affected by the process used for manufacture. A brief explanation of the process used will therefore help the reader. In this analysis, 1-1/2-inch-thick particleboard is made on a 4-foot-wide by 24-foot-long multiplaten hot-press with 20 openings. The press completes five cycles each hour, and each cycle consists of 10 minutes' curing time and 2 minutes for loading and unloading. The particleboard has a specific gravity of 0.6. Six percent uncatalyzed phenolic resin (based on ovendry weight of wood in the particleboard) is used in the face layers (each face is 1/4 inch thick), and 6 percent catalyzed phenolic resin is used in the core layer (1 inch thick). Wax is used at a rate of 0.5 percent throughout the particleboard. The particleboard is cut into strips 1-1/2 inches thick by 2-1/2 inches wide and 8 feet long to serve as cores for COM-PLY studs.

Veneer, 1/4 inch thick by 8 feet wide, is rotary-cut on a standard veneer lathe. After drying, the veneer is passed through a clipper with knives equally spaced 1-1/2 inches apart around a cylinder; these knives clip the veneer into strips 1/4 inch thick, 1-1/2 inches wide, and 8 feet long. Then the veneer strips are graded, sorted, and automatically stacked vertically in feeder bins.

The last step in the process is laminating the veneer strips to the edges of the particleboard cores with a phenol-resorcinol laminating adhesive. The veneer strips and particleboard cores are automatically fed from bins into a glue spreader. Glue is spread on one surface of the veneer and sprayed on each edge of the particleboard core at a minimum rate of 40 lb/Mft^2 of glueline. Therefore, the bondline between the veneer and the particleboard core contains twice as much glue as the bondline between veneers. After the glue is spread, the veneers are automatically turned on edge in their final position against the core edges and the assembly is transferred laterally into a lumber edge-bonding machine. The edge-bonding machine could utilize heated platens or radio frequency (RF) curing. In this study, four RF-curing edge-bonding machines were required to balance the production rate of the particleboard press. After the veneers are laminated to the particleboard cores, the studs are hot-stacked for final curing. Later, studs are run through one machine to ease the edges and a second machine to label the edges according to use designation. Then the studs are banded together in packages and stored in the warehouse until shipped to customers.

INVESTMENT REQUIREMENTS

Land

The total land required was assumed to be 30 acres and cost $8,950 per acre; thus, total land cost would be $268,500. Thirty acres of land is a generous estimate; a 15-acre site would be adequate when a company can maintain a low inventory of logs. In this study, the log inventory was assumed to be a 2-month supply, which would require the larger site. Land-developing costs such as engineering, overhead, and contingencies were assumed to be $13,410. Thus, the total cost of land and development was $281,910.

Buildings

A main building with 150,000 square feet, constructed at a cost of $8.40 per square foot, and miscellaneous small buildings with 7,000 square feet, constructed at a cost of $10.98 per square foot, resulted in costs of $1,260,000 and $76,900 for the structures. Engineering design, construction overhead, and contingencies added $500,000 to the basic building cost, for a total of $1,836,900 for buildings.

Facilities

Cost of facilities to be added to the buildings and grounds in order to make the plant operational are:

	Cost (dollars)
Site preparation	30,000
Roads, parking, and paving	30,000
Outside fire protection	48,000
Outside lighting	3,600
Outside piping (water supply and sewer)	12,000
Waste disposal	6,000
Fuel storage (gas and diesel tanks and pumps)	6,000
Inside electrical equipment (installed)	528,000
Inside piping (air, water, sewer)	43,200
Engineering, construction overhead, and contingencies	651,250
Total	1,358,050

Machinery

In this study, it was assumed that new machinery was purchased. Table 1 is a list of machinery and machinery costs for the COM-PLY stud factory. The number and size of machines required depend on the flow of materials through the factory, a topic discussed later in this report. The total cost for machinery in this analysis is $8,136,075.

Cash

In this analysis we assume that cash in the amount of 2 months' payroll is sufficient to meet the payroll, provide petty cash, and otherwise meet the cash needs of the business. In a later section, we shall show that the annual labor costs in 1975 would be $2,268,024 if the plant were operating at 100 percent capacity. Thus, cash required was assumed to be $378,004.

Table 1.--Machinery and machinery cost for a COM-PLY stud factory

Machinery or associated item	Cost
	Dollars
Log storage and handling equipment (unloaders, storage skids, sprinkling, and facilities)	182,250
Log barking equipment	445,000
Machinery foundations and supports (installed)	187,000
Block handling equipment and steam vault	238,000
Boiler	189,000
Log conveyors to lathe and foundation (installed)	41,850
Lathe and charger (installed)	261,900
Trays and tripples (installed)	75,600
Green clipper (installed)	96,000
Green veneer sorting line (installed)	92,000
Green veneer conveyor	7,400
Green veneer chipper and conveyor (installed)	71,550
Core chipper (installed)	52,650
Bark conveyor (installed)	48,600
Chip handling facility	48,600
Dryer (installed)	545,000
Dryer feeder	58,320
Dryer unloader	34,630
Moisture meter	6,750
Dry sorting chain	13,500
Dry veneer strip clipper	33,750
Dryer emission control equipment	36,450
Flaker	67,500
Fiber dryer	472,500
Fiber dryer emission control equipment	20,250
Fiber screen	8,100
Glue mixing, pumping, and metering equipment	22,950
Two blenders (installed)	83,700
Forming felter and caul line	893,025
Particleboard press (4 ft. x 24 ft.--20 openings)	2,059,425
Board stacker and conveyor	218,700
Core-cutting saw with feeder and bins	96,600
Laminating glue spreader	81,000
Stud-laminating machines (installed) (4 RF curing or 6 lumber edge-bonding machines)	575,000
Eased edge machine	56,700
Inspection line	2,700
Labeling and marking machine	1,350
Packaging and strapping machine	6,075
Forklifts and carts	87,750
Air compressor (installed)	44,550
Maintenance equipment and small tools	67,500
Spare parts and quality control equipment	70,200
Sweeper and yard truck	25,650
Storage tanks	81,000
Storage bins	54,000
Air conveyers (blowers, cyclones, piping)	113,400
Freight in for machinery	160,650
Total	8,136,075

Inventory

Investment is required to buy raw materials and cover cost of materials being processed and in finished products awaiting shipment. In this study, it was assumed that one-sixth of the annual cost of raw materials for a factory operating at full capacity would be sufficient to cover all requirements for inventory investment. It will be shown in other parts of this report that the total annual cost of raw materials for this study is $13,232,010. Therefore, the investment required for inventory would be $2,205,335.

Accounts Receivable

A considerable investment is required to cover sales to customers who do not pay immediately for the products purchased. Such customer accounts--accounts receivable--may typically be paid in 10 to 60 days. The average collection period from customer sales was assumed to be 30 days. Investment to cover accounts receivable was considered to be 1 month (30 days) of sales. Sales will vary with the unit price received for products and the quantity produced each year. Three unit prices were used in this study; but at an average first-year sales price of $130/M board feet, there would be sales of $24,710,400 per year. For this study, the investment required for accounts receivable would be $2,059,200.

Contingency

The investment for any individual item such as land or buildings may vary from the amounts assumed or there could be investments for items that might not be evident until factory construction and operation begins. Therefore, to be on the safe side, a contingency investment amounting to 5 percent of all other investments has been used in this analysis. The total of all investments up to this point is $16,255,424. Five percent of $16,255,424 is $812,771, which is the contingency investment for this study. The time when an investment is made is important in an economic analysis. Cash invested in a factory could also have been invested in securities and thus be earning interest. In this study, we assume that the major capital investments would be made during the first 3 years of factory operation. Table 2 shows the amounts and timing of investments made for this study when an average unit price of $130/M board feet is received for COM-PLY studs in 1975. The total investment for a new COM-PLY stud factory is $17,068,195.

FLOW OF MATERIALS

Forest products manufacturers with whom we worked in making this study said that creditability of the results would only be as good as the assumptions made about manufacturing cost. They said if detailed information is provided in this study, then they could use the information to make similar studies of their own by adjusting our assumptions to fit their own manufacturing operations. This section on flow of materials contains much of the detailed information upon which operating costs are based and may be skipped by readers more interested in results of the study.

Once the size and operating speed of the particleboard press has been selected, it is possible to calculate the flow of materials through the factory. Table 3 provides some of the specific assumptions made with regard to particleboard manufacture. Maloney (1973) has shown that 1-1/2-inch-thick particleboard could be cured in a minimum of 10 minutes with catalyzed phenolic resin and a platen temperature of 400° F. The catalyzed resin is needed only in the core of the particleboard because the face layers will reach curing temperatures in less than 10 minutes with uncatalyzed resin. About 1-1/2 minutes are typically required for press loading, unloading, and closing. Therefore, 11-1/2 minutes would be the minimum cycle time for making 1-1/2-inch-thick particleboard. To be on the safe side, cycle time was rounded to 12 minutes or five cycles per hour.

Table 2.--Net investment required for the first 3 years of factory operation

	Beginning of first year	End of first year	End of second year	End of third year	Total
	- - - - - - - - - - - -	- - - - -	-Dollars-	- - - - - - -	- - - - - - -
Land	281,900	0	0	0	281,900
Buildings	0	612,300	1,224,600	0	1,836,900
Facilities	0	1,086,400	271,600	0	1,358,000
Machinery	0	2,712,000	5,424,100	0	8,136,100
Cash	0	126,000	252,000	0	378,000
Inventory	0	735,100	735,100	735,100	2,205,300
Accounts receivable	0	686,400	686,400	686,400	2,059,200
Contingency	62,800	150,000	250,000	350,000	812,800
Net investment	344,700	6,108,200	[1]8,843,700	1,771,500	17,068,200

[1] This total differs from the values in the column above because of rounding.

Table 3.--Values assumed for production variables in order to calculate flow of materials through the particleboard section of the COM-PLY stud factory

Variable	Value			
	Feet	Number	Amount	Percent
Net width of press	4			
Net length of press	24			
Press openings		20		
Press cycles per hour		5		
Allowance for width trim	.35			
Allowance for length trim	.35			
Specific gravity of particleboard			.6	
Resin solids in face layer of board				6
Resin solids in core layer of board				6
Catalyst in face layer of board (liquid basis)				0
Catalyst in core layer of board (liquid basis)				6
Wax solids in face layer of board				.5
Wax solids in core layer of board				.5
Other solids in resin used in face layer (percent of resin solids)				29.3
Other solids in resin used in core layer (percent of resin solids)				29.3
Solids in catalyst used in face layer				66.0
Solids in catalyst used in core layer				66.0
Average specific gravity of wood supply			.59	
Ratio of wood weight in core to wood weight in face			2	

On the basis of the assumptions in table 3, we used a computer to calculate the hourly flow of materials through the particleboard section of the factory (table 4). In making the calculations, we used Koch's (1972) value of 1.15 for the ratio of green wood volume to dry wood volume.

Table 4.--Flow of materials through particleboard section of COM-PLY stud factory at 100 percent efficiency

Material	Flow		
	Cubic feet per cycle	Cubic feet per hour	Pounds per hour
Particleboard pressed	264.8	1,324	
Ovendried wood in face layer			14,699
Ovendried wood in core layer			29,398
Solid ovendried wood in face layer		399	
Solid ovendried wood in core layer		798	
Green wood from peeling residue to be chipped			87,742
Green wood from top logs too small to peel into veneer			7,066
Resin solids in face layer			882
Resin solids in core layer			1,764
Liquid catalyst in face layer			0
Liquid catalyst in core layer			105.8
Wax liquid emulsion in face layer			153
Wax liquid emulsion in core layer			306
Other solids from resin and catalyst in face and core layers			775.2
Water in particleboard after pressing			1,763.9

At the factory, the particleboard is cut into stud cores with a gang ripsaw having a kerf of 0.125 inch. Computations show there would be 5,400 cores produced per hour. Net requirements for veneer are 4 square feet per stud, but 5 percent waste must be added to obtain the gross requirements for veneer. Table 5 shows the computed hourly quantities of stud cores, veneer, veneer logs, and peeling residues processed at the factory by converting tree-length southern pine into veneer.

These quantities are based on a study by McAlister and Taras (1978), who provided information on the dry-volume yields of veneer per acre from southern pine timber. For their study, representative loblolly and slash pines in natural stands were cut into veneer blocks and peeled into veneer at a commercial plywood plant. The grade and dry volume of veneer produced from the peeler blocks were tallied. Table 6 shows the yields of products produced from an acre of typical southern pine timber.

Table 6 is important in demonstrating total-tree utilization and computing the flow of materials in a factory. Veneer of grade C or better has sufficient strength to be used in COM-PLY studs. Notice that the dry volume of C and better veneer (412.6 ft^3) is 30.5 percent of the total dry tree volume (1351.6 ft^3) in that acre. A COM-PLY stud with 1/4-inch-thick veneer contains 30 percent veneer (assuming 5 percent waste veneer) by volume. Thus, a COM-PLY stud factory could utilize all of the C grade and better veneer in a typical stand and convert the rest of the wood to particleboard, thereby providing total-tree utilization.

Table 5.--Hourly flow of materials through veneer and chip-preparation sections of a COM-PLY stud factory at 100 percent efficiency

Material	Amount per hour				
	Number	Square feet	Cubic feet	Linear feet	Pounds
Stud cores produced	5,400				
Dry veneer required for above stud cores including 5 percent waste		22,680			
Dry veneer required			473		
Green veneer logs required			1,507		
Green logs to be barked				2,728	
8-foot peeler blocks to be peeled	341				
Peeling residues produced from cores, round-up, and spur trim			964		
Green wood required in addition to peeling residues to supply wood particles for particleboard cores (assumed to come from tops of trees above height where peeler blocks occur)			414		
Small logs from upper tree stems to be barked for wood particles				1,737	
12-foot-long small logs to be barked	145				
Water removed from green veneer during drying					20,005
Water removed from green wood chips during drying					50,711

One of the most important uses of table 6 is to compute ratios for the flow of veneer, veneer residues, and linear feet of logs through the factory. Some of the more important ratios are shown in table 7. For example, table 7 shows that there will be 2.04 cubic feet of green peeling residues, D veneer, and fishtail produced for each dry cubic foot of dry C and better veneer produced. The ratios shown in table 7 were used in the computer analysis to obtain hourly flow of wood products shown in table 5.

For production of 5,400 studs per hour and spread rates of 40 lb/Mft^3 of glueline between veneers and 80 lb/Mft^3 between veneers and the core, the hourly quantities of phenol-resorcinol adhesive including catalyst can be computed. Four hundred thirty-two pounds of mixed adhesive would be required per hour on veneer-to-veneer gluelines and 864 pounds per hour on veneer-to-particleboard gluelines.

OPERATING COSTS

Operating costs are needed to determine annual net earnings or cash proceeds that will result from the investment. Operating costs provide insight on how the cost of producing COM-PLY studs compares with the cost of producing sawn lumber studs. The following discussion is concerned with operating costs to produce COM-PLY studs at 1975 price levels. In this study, it is assumed that the factory operates 6 days per week and 50 weeks per year. Out of each 24-hour day, it is assumed that there are 22 hours of useful work. Efficiency is thus about 92 percent or 6,600 hours of production per year. Such high efficiency is possible because only a single item is being made and the setup and startup times will be small. Normally, plants that make a variety of particleboards have efficiencies of about 85 percent.

Table 6.--Average dry volume of veneer and residues per acre in a typical, natural stand of southern pine[1]

Item	Yield per acre	Proportion of total stand volume per acre
	Cubic feet	Percent
A & B veneer	121.5	9.0
C veneer	291.1	21.5
D veneer	182.1	13.5
Total full-length veneer	594.7	44.0
Fishtail	43.6	3.2
Total veneer	638.3	47.2
Peeling residue	507.5	37.6
Total block volume	1,145.8	84.8
Top log residue	205.8	15.2
Total tree volume	1,351.6	100.0

[1] From McAlister and Taras (1978). Based on per-acre values for number of trees, block volume, and tree volume in a typical, natural stand of southern pine.

Unit Materials Cost

Wood

Potential manufacturers of COM-PLY studs have several sources of wood for their factory. One method of purchasing wood is to buy stud-grade veneer and the lowest-cost mill residue for the wood particles in the particleboard. Another method is to purchase full tree-length timber and process it. If the second method is used, veneer of the needed quality must be pulled from that portion of the tree with a nominal diameter of 8 inches or larger; then the peeling residues and portions of the tree too small to peel must be converted to wood particles for the particleboard. We have used the second method in this study. Of the many methods possible for purchasing wood for COM-PLY studs, the one that results in the highest internal rate of return on the investment should be used. Purchasing full-tree-length timber has distinct advantages which offset its disadvantages.

One advantage of using full-tree-length timber is that the parts of the tree too small to peel, as well as the peeling residues from the veneer operation (cores, roundup, spur-trim), are cleaner and of higher quality than mill residues typically used to make particleboard. Practically no wood waste is generated from such a wood supply. In this study, we assumed that 5 percent waste and scrap would be lost during veneer peeling and particle chipping. In a plywood plant, wood losses are usually higher because of waste generated by trimming veneer into widths for 4-foot-wide panels, trimming the panels, and sanding.

Table 7.--Ratios used for computing the flow of veneer, veneer residues, and linear feet of logs through a COM-PLY stud factory[1]

Ratio	Value
Volume of green peeling residue, D veneer, and fishtail to volume of dry C and better veneer	2.04
Linear feet of green peeler log per cubic foot of green peeler log	[2] 1.44
Linear feet of small green logs from upper part of tree to cubic foot of green peeler log	[2] 4.20
Volume of green peeler log to volume of dry C and better veneer	3.19

[1] From McAlister and Taras (1978). The values in their study are for dry volumes. The dry volumes of peeling residue and block volumes were increased by 15 percent to obtain the green volumes used in computing the ratios in this table.

[2] From unpublished studies by G. A. Koenigshof on file at the Forestry Sciences Laboratory, Athens, Georgia.

The most important advantage of using full-length trees is that an optimum size and shape of wood particle can be made from peeling residues and those parts of the tree too small to peel. Particles made by flaking roundwood and then milling the wide flakes into narrow ones are ideal for COM-PLY studs (fig. 2). Much less resin is required to coat flakes up to 2 inches long than to coat particles made from sawmill residues, which typically contain a large percentage of fine material. Although more energy is required to dry flakes and splinters made from green wood than to dry sawmill residues, this higher energy cost is more than offset by the reduced amounts of waste, scrap wood, and resin.

In 1975, southern pine saw logs cost about $117.25/M board feet (Doyle scale) delivered to the mill, and oak and gum saw logs cost $76.50 and $79.93/M board feet (U.S. Dep. Agric. 1977). When converted to cost per green cubic foot, these prices are approximately $0.53 for southern pine, $0.34 for oak, and $0.36 for gum. Full-tree-length logs could probably be obtained for less cost per cubic foot because harvesting and hauling costs would be somewhat less than for saw logs. Assuming COM-PLY studs would be made from half hardwood and half southern pine, the 1975 cost per cubic foot for green saw logs delivered to the mill is about $0.44. For full-tree-length logs, green mixed pine and hardwood could probably be obtained for about $0.40 per cubic foot in 1975. Since wood shrinks about 15 percent when dried and we assumed that 5 percent is wasted in the factory, the cost of dry wood in the stud is about $0.483 per cubic foot. For the 10-year investment period in this study, costs of green wood were assumed to increase at a compound rate of 7 percent per year, as tabulated below:

Yearly period	Cost of green wood (dollars/cubic foot)
1	0.400
2	.428
3	.458
4	.490
5	.524
6	.561
7	.600
8	.642
9	.687
10	.735

Typically, prices of softwood timber fluctuate with prices of softwood lumber. However, when prices of pine sawtimber are rising rapidly because of strong demand, the price of hardwood usually remains relatively constant. Therefore, the cost per cubic foot of a mixture of hardwoods and softwoods would probably not escalate as rapidly in a period of strong demand as the cost of softwoods only.

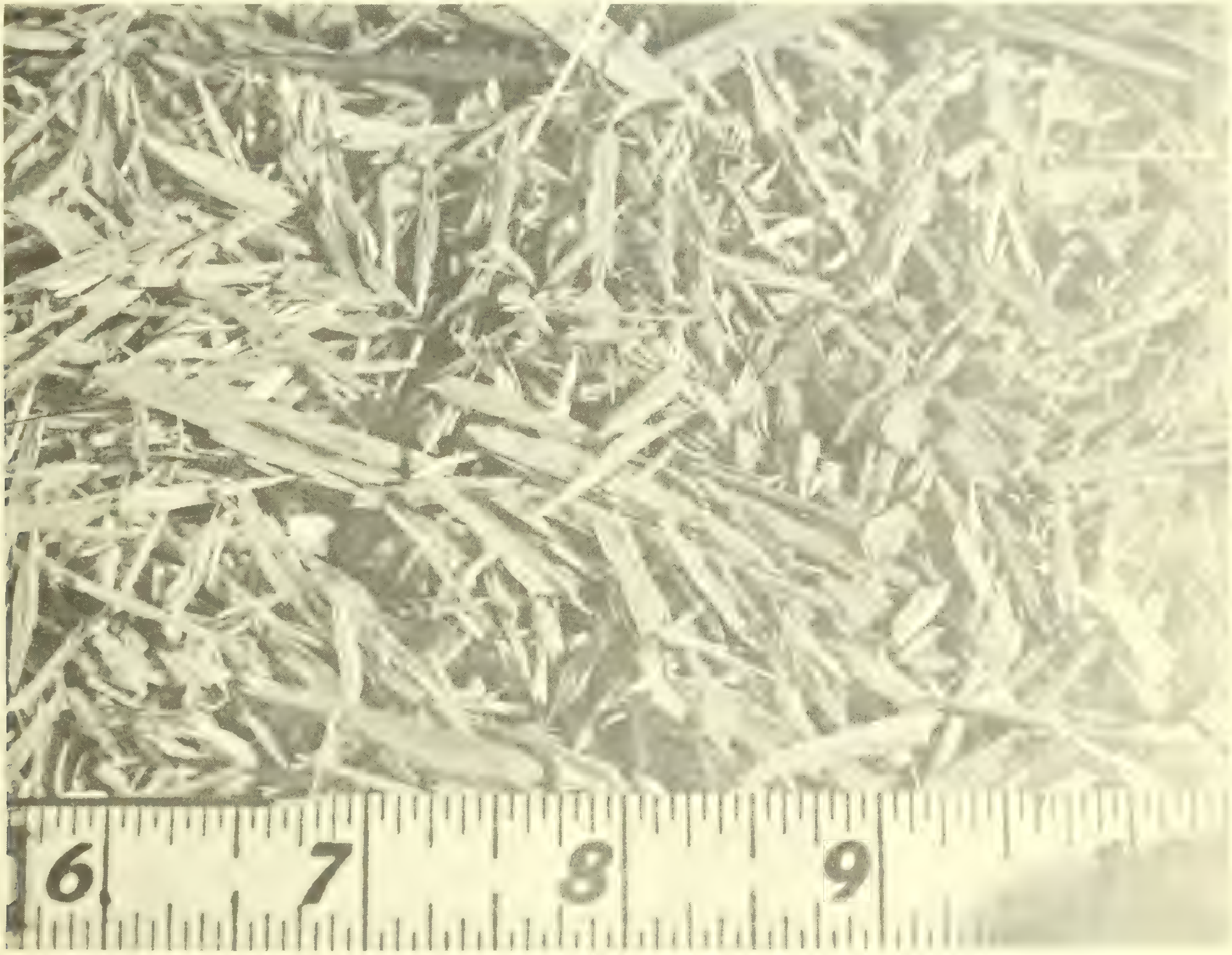

Figure 2.--Flake-type particles made from peeler cores; they can be coated satisfactorily with 6 percent resin.

The volume of veneer in a stud is about 20 to 30 percent of the stud volume, whereas the volume of C and better veneer in an average mixture of southern pine trees is slightly over 30 percent. In other words, there is a slight surplus of veneer generated in making COM-PLY studs when full-length southern pine timber is used. Thus, there are opportunities to reduce wood cost by supplementing the factory's raw wood supply with low-cost, high-quality residues, such as waste from a plywood mill.

Veneer for COM-PLY studs does not require high-quality timber. This study is based on veneer grades and yields of southern pine from timber of No. 2 sawlog quality.

Potential manufacturers of COM-PLY studs must consider all the factors discussed and select the right combination from the wood supply at their disposal when making their own analysis of economic feasibility. However, the quantity of resin required to make a stud that will meet the quality standards for the product is greatly influenced by the type of wood used to make the particles.

Particleboard Resin

Figure 3 shows industrial average prices for the phenolic resin used in particleboard on a 100 percent solids basis. From 1955 to 1973, the price of phenolic resins steadily declined. Then in 1974 the price rose drastically as a result of shortages of petrochemicals and plant capacity. This study is based on the 1975 price of $0.31 per pound for phenolic resin and an estimated price increase at a compound rate of 5 percent per year.

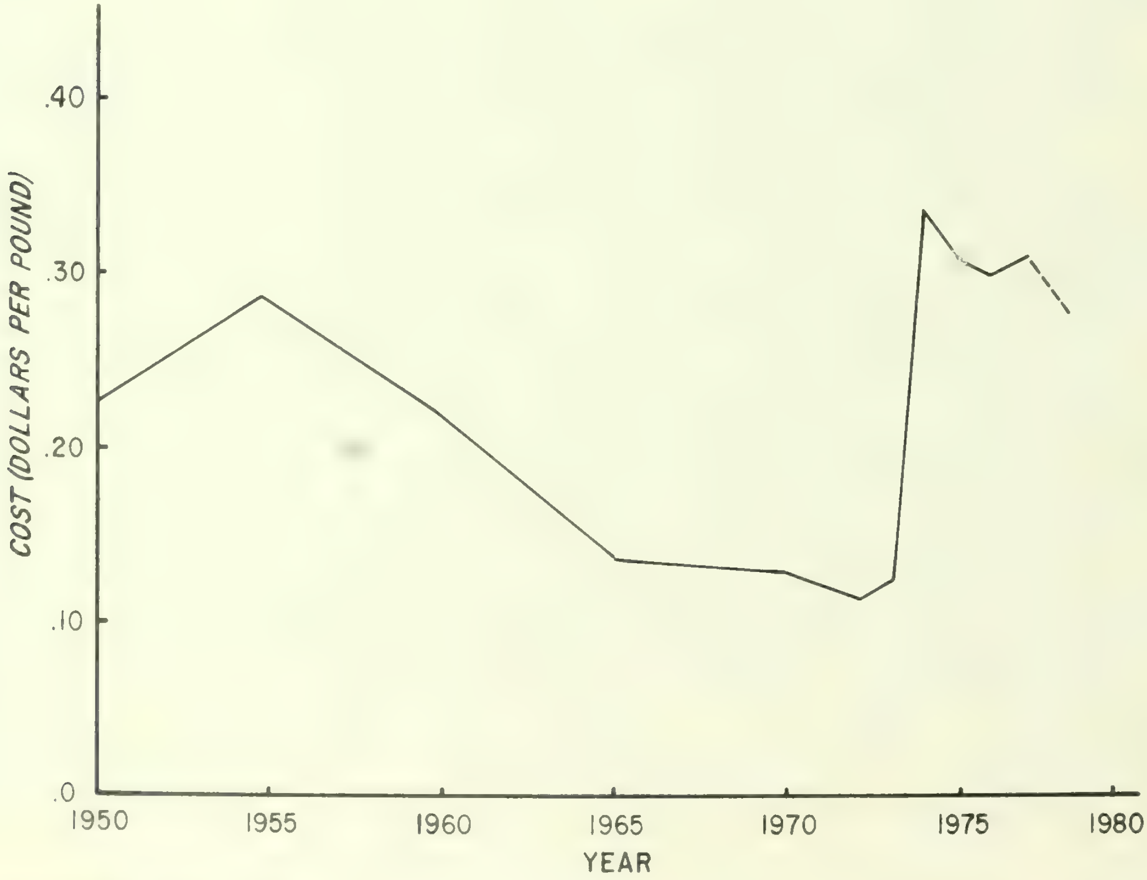

Figure 3.--Price of phenolic resin per dry pound on a 100 percent solids basis.

Resin Catalyst

Research performed for the Forest Service at Washington State University showed that phenolic resin binders for particleboard can be cured in 10 minutes at a platen temperature of 400° F if a catalyst is used to accelerate curing. Assuming that the time for press loading, closing, opening, and unloading does not exceed 2 minutes, it is possible to have a 12-minute press cycle (the time assumed in this study) when a catalyzed resin binder is used. The 1975 price for the catalyst was $0.48 per liquid pound. The amount of liquid catalyst required is 6 percent of the dry resin binder used. Catalyst prices are also estimated to increase at a compound rate of 5 percent per year.

Particleboard Wax

Liquid wax emulsions are added to particleboard in order to reduce thickness swelling when the particleboard is soaked in water for short periods. These emulsions, roughly half wax solids, were priced at $0.09 per liquid pound in 1975. In this study, we used this 1975 price for wax emulsion and assumed it would increase at a compound rate of 5 percent per year.

Laminating Adhesive

Phenol-resorcinol adhesives that cure at room temperature are widely used for laminating large structural timbers. Such adhesives are a mixture of five parts liquid phenol-resorcinol resin and one part paraformaldehyde hardener by weight. Cost of these adhesives when mixed was about $0.50 per liquid pound in 1975. The adhesives contain a large percentage of resorcinol in order to allow curing at room temperature in a few hours, but the adhesive can be cured with high-frequency heating equipment in just a few minutes. By reducing the amount of resorcinol resin and increasing the amount of phenolic resin, the cost could be reduced to about $0.25 per liquid pound. Two major manufacturers said that they would supply a laminating resorcinol-modified phenol adhesive that could be cured with high-frequency heat at a cost of only $0.25 per mixed liquid pound in 1975. We adopted this price for the present study and assumed that prices would increase at a compound rate of 5 percent per year.

Total Materials Cost

Total annual cost for materials is found by multiplying the quantity of materials flowing per hour times 6,600 hours per year times the unit price of the materials (table 8). This cost was calculated to be $13,232,010.

Labor Cost

Labor costs vary with the levels of skill demanded of workers, fringe benefits paid, and geographic location. Labor wages have been rising rapidly since 1961. Table 9 was developed from industry reviews to show the wage assumptions used in this study for various levels of skill from 1975 through 1985. We assumed that the factory would be built in Arkansas and pay wages including fringe benefits at the prevailing rates in that State. Table 10 lists all of the job descriptions, number of workers, number of shifts worked, wage rate paid, hours worked per day, and daily labor cost for each operation. Total daily labor cost was calculated to be $7,560.08. This sum multiplied by the 300 days worked per year is the total annual labor cost. At full production capacity, the annual labor cost at the 1975 rate is $2,268,024.

The annual cost for labor will escalate exponentially from year to year, as indicated by the growth rate in table 9. Of course, the amount of labor required during the beginning years will be less than when the plant reaches full production. In fact, during the first-year construction period (1975), there will be no direct labor cost.

Table 8.--Annual cost of materials for a COM-PLY stud factory

Item	Flow of materials per hour	Time worked per year	Unit price	Total annual cost
		Hours	Dollars	Dollars
Wood (green-tree length)	1,921 ft^3	X 6,600	X 0.40/ft^3	= 5,071,440
Particleboard resin	2,646 lb(dry)	X 6,600	X .31/lb	= 5,413,716
Particleboard catalyst	106 lb(liquid)	X 6,600	X .48/lb	= 335,808
Particleboard wax	459 lb(liquid)	X 6,600	X .09/lb	= 272,646
Laminating adhesive	1,296 lb(liquid)	X 6,600	X .25/lb	= 2,138,400
Total				13,232,010

Table 9.--Estimated labor costs (including fringe benefits) of operating a COM-PLY stud factory in Arkansas from 1975 through 1985[1]

Year	Skill level of workers		
	Skilled	Semi-skilled	Unskilled
	Dollars per hour	Dollars per hour	Dollars per hour
1975	4.96	4.54	4.02
1976	5.23	4.78	4.24
1977	5.51	5.05	4.47
1978	5.81	5.32	4.71
1979	6.13	5.61	4.97
1980	6.46	5.92	5.24
1981	6.82	6.24	5.52
1982	7.19	6.58	5.82
1983	7.58	6.94	6.14
1984	7.99	7.31	6.47
1985	8.42	7.71	6.83

[1] Wages escalate by the amount $10^{0.023(n-1)}$ where n is 1 to 11 for years 1975 through 1985.

Energy Cost

A COM-PLY stud factory requires two types of energy for its operation--electrical and thermal. Some operations require both electrical and thermal energy, while others require only one. Actual energy costs depend on the volume of materials being processed, efficiency of the machinery, fuel type, and fuel costs.

Table 11 lists the important energy-using operations in a COM-PLY stud factory and shows the estimated quantities of electrical and thermal energy for a given production unit per hour. For example, table 11 shows that drying chips requires

Operations or job	Workers	Shifts	Hourly wage rate[1]	Time worked per day	Daily cost for labor
	- - - No.	- -	Dollars	Hours	Dollars
Log scaler	1	1	4.96	8	39.68
Log lift driver	2	1	4.54	16	72.64
Barker operator	1	1	4.54	8	36.32
Conveyor chaser	1	1	4.02	8	32.16
Fireman	1	3	4.54	24	108.96
Cut-off sawyer	1	1	4.54	8	36,32
Helper	1	1	4.02	8	32.16
Log sorter	1	1	4.96	8	39.68
Jitney driver (veneer)	1	1	4.54	8	36.32
Grinding room man	1	1	4.96	8	39.68
Lathe operator	1	3	4.96	24	119.04
Clipperman (green)	1	3	4.54	24	108.96
Offbearer	3	3	4.02	72	289.44
Jitney driver (veneer)	1	3	4.54	24	108.96
Dryer tender	1	3	4.54	24	108.96
Veneer grader	4	3	4.54	96	435.84
Dryer feeder & offbearer	3	3	4.02	72	289.44
Strip clipperman	3	3	4.54	72	326.88
Stacker	8	3	4.02	192	771.84
Glue mixer	1	3	4.54	24	108.96
Lam machine & saw operator	4	3	4.54	96	435.84
Feeders-Laminator	8	3	4.54	192	871.68
Eased edger	1	3	4.96	24	119.04
Inspector	2	3	4.96	48	238.08
Jitney driver (general)	1	3	4.54	24	108.96
Jitney driver (warehouse)	1	1	4.54	8	36.32
Car loader	3	1	4.54	24	108.96
Splitter & slasher	1	1	4.54	8	36.32
Chipper operator	1	1	4.54	8	36.32
Clean up (screen)	1	1	4.02	8	32.16
Flaker operator	1	3	4.54	24	108.96
Hammermill operator	1	3	4.54	24	108.96
Dryer & screen operator	1	3	4.54	24	108.96
Resin mixer	1	3	4.54	24	108.96
Former operator	1	3	4.96	24	119.04
Press operator	1	3	4.96	24	119.04
Trimmer & cooler	1	3	4.54	24	108.96
Core cutter & stacker	4	3	4.54	96	435.84
Jitney driver (particleboard)	1	3	4.54	24	108.96
Millwright	1	3	4.96	24	119.04
Millwright helper	1	3	4.54	24	108.96
Electrician	1	3	4.96	24	119.04
Cleanup	1	3	4.02	24	96.48
Foreman	1	3	8.25	24	198.00
Superintendent	1	1	10.00	8	80.00
Machinist	1	1	4.96	8	39.68
Pipefitter	1	1	4.96	8	39.68
Storeroom man	1	1	4.54	8	36.32
Watchman	1	3	4.02	24	96.48
Strapper operator	1	3	4.02	24	96.48
Shipping clerk	1	1	4.54	8	36.32
Total				1,664	7,560.08

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[1] Hourly rate includes 25 percent for taxes and fringe benefits.

Table 11.--Energy required to make COM-PLY studs

Production operations	Production units per hour	Electrical energy per unit	Thermal energy per unit
		kWh	Btu
Barking logs	Linear feet of logs	0.004 to 0.012	-
Hogging waste wood and bark	Green tons	20 to 40	-
Conveying chips, logs, etc.	Green tons	35	-
Steaming peeler blocks	Green tons	-	110,000
Log cut-off and slasher saws	Linear feet of logs	0.002	-
Log-sorting deck equipment	Linear feet of logs	0.003	-
Peeling veneer blocks on rotary lathe	Square feet of veneer	0.006	-
Veneer drying			
a. electrical	Square feet of veneer	0.007	-
b. thermal	Pounds of water removed	-	1,500
Conveying veneer	Square feet of veneer	0.003	-
Chipping round and waste wood into chips	Green tons of wood	17 to 40	-
Hammermilling chips into particles	Green tons of chips	15 to 25	-
Drying chips			
a. electrical	Green tons	18	-
b. thermal	Pounds of water removed	-	1,800
Screening chips	Dry tons of chips	0.3 to 0.5	-
Blending particles with resin and resin mixing	Dry tons of particles	8	-
Forming particleboard matt	Dry tons of matt	5	-
Prepress matt	Square feet of matt	0.004	-
Press matt into particleboard			
a. electrical	Dry tons of matt	6	-
b. thermal			
(1) heat matt	Dry tons of matt	-	120,000 to 160,000
(2) heat cauls (if used)	Dry tons of matt	-	80,000 to 160,000
(3) heat losses			
(a) water evaporation	Dry tons of matt	-	80,000 to 160,000
(b) radiation	Dry tons of matt	-	6,000 to 12,000
(c) convection	Dry tons of matt	-	4,000 to 12,000
Finish studs	Number of studs	0.001	-
Laminate studs	Number of studs	0.003	150

18 kilowatt hours of electrical energy for every green ton of chips processed and 1,800 Btu of thermal energy for every pound of water removed from the chips. The values for energy shown in table 11 are estimates; actual values in a factory could vary widely, depending on machine efficiency.

Table 12 shows the energy computations. For example, the amount of green wood to be chipped and dried (from table 4) is 87,742 pounds per hour of peeling residues and 7,066 pounds per hour of small top logs. The total is 94,808 pounds per hour or 47.4 tons per hour. The estimated electrical energy required for drying chips is 18 kilowatt hours per green ton (from table 11) times 47.4 green tons per hour or 853.2 kilowatt hours per hour. Table 5 shows that the amount of water removed from green chips is 50,711 pounds per hour. The estimated thermal energy required to dry the green chips is obtained by multiplying 50,711 pounds of water per hour times 1,800 Btu per pound of water removed or 91,279,800 Btu per hour. The values for electrical energy are based on full-rated horsepower of motor-driven equipment and must be reduced to 70 percent of the values shown in order to be more realistic about actual loads on the motors. For electricity costing $0.014 per kilowatt hour, the cost per year for electricity is $415,000; for thermal energy costing $0.07 per therm, the cost per year is $649,000. The total energy cost per year for this analysis is $1,064,000 in 1975. In this study the price of fuel increases at a compound rate of 5 percent per year.

Other Production Costs

There are various other costs associated with manufacture that need to be accounted for in operating a factory. These costs are best obtained from accounting records of an actual factory; the amounts shown in table 13 are rough estimates.

Sales promotion expenses were arbitrarily assumed to be 6 percent of the 1975 sales if the plant had been operating at full capacity and were distributed over the first 3 years of operation in declining amounts of 3 percent, 2 percent, and 1 percent of sales.

Depreciation Costs

Depreciation expense must be computed in order to determine the manufacturing costs for studs and taxable income and to determine return on investment. In determining manufacturing costs, the straight-line method of depreciation was used; in determining return on investment, the sum-of-the-years digit method was used. In this study, buildings, facilities, and machinery were depreciated over the 10-year investment period.

ANNUAL SALES, OPERATING CASH FLOWS, AND TOTAL MANUFACTURING COST

The purpose of this section is to determine the cash proceeds or net earnings that accrue to the business as a result of manufacturing operations. In computing net earnings, it is necessary first to compute revenue from sales and then to subtract manufacturing costs and taxes.

Some price has to be assumed for the product. In this analysis, therefore, the prices of COM-PLY studs are assumed to compete with those of sawn kiln-dried studs.

It is extremely difficult to make accurate predictions of stud prices because they fluctuate widely with various economic conditions. The average f.o.b. mill price of kiln-dried Hem-fir studs was $61.83/M board feet in 1966 and rose to $157.17/M board feet in 1976 (Evans 1976). This rise in price is about 10 percent compound growth for a 10-year period. In 1975, the average f.o.b. mill price for kiln-dried Hem-fir studs was $126.33/M board feet. The year 1975 was a period of recession, low home-building activity, and low lumber prices. We therefore estimated that stud prices would increase at a lower compound growth rate of 7 percent during the investment period from 1975 to 1985--about 3 percent less growth than during the previous 10-year period. Three price levels for COM-PLY studs in 1975 were used in the study; the first was assumed to be $123.50/M board feet, the second was assumed to be $130.00/M board feet, and the third was assumed to be $136.50/M board feet. Since 1975 was a period of relatively low lumber prices, the second price level probably most closely represents the base for the long-term price trend for studs. Table 14 shows f.o.b. mill prices for COM-PLY studs at the three levels during the investment period.

Table 12.--Estimated energy required per hour to produce COM-PLY studs[1]

Operation	Energy unit		Materials unit		Energy/hour	
					Electrical	Thermal
					kWh	Btu
Barking logs	0.006	X	4,465.0	=	26.79	
Hogging fuel	30.000	X	7.0	=	210.00	
Conveying chips	35.000	X	63.2	=	2,212.00	
Steaming blocks	110,000.000	X	59.7	=		6,567,000
Log cut-off	.002	X	4,465.0	=	8.93	
Log sorting	.003	X	4,465.0	=	13.40	
Peeling veneer	.008	X	22,680.0	=	181.44	
Veneer drying	.004	X	22,680.0	=	90.72	
Veneer drying	1,800.000	X	20,004.09	=		36,007,362
Conveying veneer	.003	X	22,680.0	=	68.04	
Flaking wood	28.000	X	47.4	=	1,327.20	
Hammermilling	20.000	X	47.4	=	948.00	
Drying chips	18.000	X	47.4	=	853.20	
Drying chips	1,800.000	X	50,711.0	=		91,279,800
Screening chips	.400	X	22.1	=	8.84	
Blending	8.000	X	22.1	=	176.80	
Forming matt	5.000	X	24.8	=	124.00	
Prepress matt	.004	X	96.0	=	.38	
Pressing matt	6.000	X	24.8	=	148.80	
Heating matt	140,000.000	X	24.8	=		3,472,000
Heating cauls	100,000.000	X	.0	=		0
Water loss	80,000.000	X	24.8	=		1,984,000
Radiation loss	9,000.000	X	24.8	=		223,200
Convection loss	8,000.000	X	24.8	=		198,400
Finish stud	.001	X	5,400.0	=	5.40	
Laminate stud	.003	X	5,400.0	=	16.20	
Laminate stud	150.000	X	5,400.0	=		810,000
Total					6,420.14	140,541,762
					X .70[2]	
					4,494.10	

[1] Factory is assumed to work 6,600 hours per year. Hourly totals for kWh and Btu must be multiplied by this value to obtain yearly totals.

[2] Electrical energy is 70 percent of total in order to account for motors not running at full rated horsepower.

Table 13.--Miscellaneous production costs in operating a COM-PLY stud factory

Cost	Amount		
	Percent of sales	Percent of land, building, and facilities cost	Salary (in 1975)
			Dollars
Production supplies	2.0		
Maintenance supplies	1.0		
Utilities	.1		
General manager			25,000
Office manager			18,000
Office clerks (three at $6,000 each)			18,000
Grade-certification fees	1.0		
Other office administrative expenses	.5		
Sales promotion	6.0		
Facilities maintenance		2.0	
Facilities taxes		.5	
Facilities insurance		.5	
Sales expense	5.0		
Contingency expense	2.0		

Table 14.--Estimated f.o.b. mill prices for COM-PLY studs during the investment period from 1975 to 1985

Year	Price level		
	(1)	(2)	(3)
	- - - - -Dollars per M board feet- - - - -		
1975	123.50	130.00	136.50
1976	132.15	139.10	146.06
1977	141.40	148.84	156.28
1978	151.29	159.26	167.22
1979	161.88	170.40	178.92
1980	173.22	182.33	191.45
1981	185.34	195.09	204.85
1982	198.31	208.75	219.19
1983	212.20	223.36	234.53
1984	227.05	239.00	250.95
1985	242.94	255.73	268.52

Given a choice between COM-PLY and conventional sawn studs at the same price, the builder probably would choose COM-PLY because they do not warp. Builders often recut 10 to 25 percent of their conventional studs into shorter lengths for use as blocking or short members because of excessive warpage. Thus, builders might even pay a premium price for COM-PLY studs, although we have not made that assumption in this study.

Table 15 shows the annual cash flows from operating a COM-PLY stud factory over the 10-year period. In this study, it is assumed that the production level of studs will be zero during the first year, 20 percent the second year, 80 percent the third year, and 100 percent the fourth year. When the factory reaches the 100 percent level, it will be operating at an efficiency of 92 percent.

The cash flows from sales in table 15 were computed by multiplying the f.o.b. mill price times the board footage of studs produced per year. There were 5,400 studs produced per hour for 6,600 hours per year, and each stud contains 5-1/3 board feet. Thus, annual production would be 190,080,000 board feet annually by the fourth year of operation.

There is some terminal salvage value for buildings, facilities, and machinery at the end of the 10-year investment period. Because this terminal salvage is revenue from a sale and is taxable, it is treated as a sales item during the last year of the investment period.

Computing the cash flows for operating costs in table 15 is similar to computing the cash flows for sales. The inflation rate was 7 percent for logs and items that were computed as a percentage of sales. Otherwise, the inflation rate used was 5 percent except for wage rates, which escalated at the rate shown in table 9. The general manager, office manager, and clerks were assumed to be hired on a full-time basis at the beginning of the second year. Sales promotion occurred only during the first 3 years, declining from $741,300 the first year to $247,100 by the third year. Only 50 percent of the facilities expense was assumed to occur the first year, but full facilities expenses occurred in subsequent years and escalated at a rate of 5 percent.

Total operating costs for purposes of computing taxable income were found by totaling the cost for raw materials, production expenses, administrative expenses, sales promotion, facilities expense, contingency expense, sales expense, and depreciation. For example, the operating cost for the fourth year, when full production had been reached, is shown as $24,901,200. Depreciation is included with the operating cost because the Internal Revenue Service allows depreciation to be deducted as an expense for tax computations. Depreciation began in the second year, when most of the investment for machinery and facilities had been made.

The taxable income is the difference between sales and total operating cost including depreciation. For the fourth year, the taxable income is $5,370,100. For this study, we assumed that the Federal tax rate is 48 percent and that there would be 4 percent additional state and local tax charges, for a total tax rate of 52 percent. Tax on income for the fourth year is $2,792,500 and after-tax profit is $2,577,600.

To obtain the net annual earnings for the fourth year, the depreciation (which was subtracted as a production cost for computing taxes) is added back to the after-tax profit. The net earnings for the fourth year are $4,225,800.

Notice that a negative income tax is shown for the first and second years. The Federal government does not make tax refunds to companies that have a loss from operating. However, for a large company, these losses could be charged off against other parts of the business that were operating profitably; therefore, they have been left in this analysis. For a company that could not write off the losses that occur during the first 2 years, there would be zero income tax and negative net earnings for both years.

Operating costs shown in table 15 can be used to compute the 1975 manufacturing cost of a stud. This cost is computed by projecting the amounts for each item during the fourth year back to the 1975 cost. For most items, the 1975 price

Item	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
	-Thousands of dollars-									
A. Sales										
COM-PLY studs	0	5,288.0	22,632.7	30,271.3	32,390.3	34,657.6	37,083.6	39,679.5	42,457.1	45,429.1
Terminal salvage	0	0	0	0	0	0	0	0	0	206.0
Total	0	5,288.0	22,632.7	30,271.3	32,390.3	34,657.6	37,083.6	39,679.5	42,457.1	45,635.1
B. Raw materials										
Logs	0	1,085.3	4,645.0	6,212.7	6,647.6	7,112.9	7,610.8	8,143.6	8,713.6	9,323.6
Particleboard resin	0	1,136.9	4,774.9	6,267.0	6,580.4	6,909.4	7,254.9	7,617.6	7,998.5	8,398.4
Particleboard catalyst	0	70.5	296.2	388.7	408.2	428.6	450.0	472.5	496.1	520.9
Particleboard wax	0	57.2	240.4	315.6	331.3	347.9	365.3	383.6	402.8	422.9
Laminating adhesive	0	449.1	1,886.1	2,475.5	2,599.2	2,729.2	2,865.7	3,008.9	3,159.4	3,317.4
Total	0	2,799.0	11,842.6	15,659.5	16,566.7	17,528.0	18,546.7	19,626.2	20,770.4	21,983.2
C. Production expenses										
Direct labor	0	1,195.7	2,521.4	2,658.6	2,803.2	2,955.6	3,116.4	3,285.8	3,464.6	3,653.0
Power and fuel	0	223.5	938.8	1,232.2	1,293.8	1,358.5	1,426.4	1,497.7	1,572.6	1,651.2
Production supplies	0	105.8	452.7	605.4	647.8	693.2	741.7	793.6	849.1	908.6
Maintenance supplies	0	52.9	226.3	302.7	323.9	346.6	370.8	396.8	424.6	454.3
Utilities	0	5.3	22.6	30.3	32.4	34.7	37.1	39.7	42.5	45.4
Total	0	1,583.1	4,161.8	4,829.1	5,101.0	5,388.5	5,692.3	6,013.6	6,3[illegible]3.3	6,712.5
D. Administrative expenses										
General manager	0	26.2	27.6	28.9	30.4	31.9	33.5	35.2	36.9	38.8
Office manager	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Clerks (3)	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Grade-certification fees	0	52.9	226.3	302.7	323.9	346.6	370.8	396.8	424.6	454.3
Other	0	26.4	113.2	151.4	162.0	173.3	185.4	198.4	212.3	227.1
Total	0	143.4	406.7	524.7	560.0	597.7	638.0	681.0	727.0	776.1
E. Sales promotion	741.3	[illegible]	247.1	0	0	0	0	0	0	0
F. Facility expenses										
Maintenance	34.8	[illegible]	76.7	80.5	84.5	88.7	93.2	97.8	102.7	107.9
Taxes	8.7	[illegible]	19.2	20.1	21.1	22.2	23.3	24.5	25.7	27.0
Insurance	8.7	[illegible]	19.2	20.1	21.1	22.2	23.3	24.5	25.7	27.0
Total	52.2	[illegible]	115.0	120.7	126.8	133.1	139.8	146.8	154.1	161.8
G. Contingency expenses	0	105.8	452.7	605.4	647.8	693.2	741.7	793.6	849.1	908.6
H. Sales expense	0	264.4	1,131.6	1,513.6	1,619.5	1,732.9	1,854.2	1,984.0	2,122.9	2,271.5
I. Cost of operations (B+C+D+E+F+G+H+L)	793.5	7,[illegible]9.6	20,211.7	24,901.2	26,064.0	27,339.4	2[illegible]2.7	30,0[illegible]9.3	31,594.8	33,225.6
J. Taxable income (A-I)	-793.5	-2,2[illegible]1.6	2,421.0	5,370.1	6,326.3	7,3[illegible].2	[illegible].9	9,[illegible].2	10,[illegible]2.2	12,409.4
K. Income tax (52% X J)	-412.6	-1,181.2	1,2[illegible]	2,792.5	3,289.7	3,[illegible]21.0	[illegible],3[illegible].3	[illegible]97.[illegible]	5,[illegible]8.4	6,452.9
L. Depreciation										
Machinery	[illegible]	[illegible]9.3	1,3[illegible]	1,18[illegible]	1,0[illegible]	[illegible]87.[illegible]	[illegible]9.6	[illegible]91[illegible]	[illegible].8	295.9
Facilities	[illegible]	[illegible]	[illegible]2[illegible]	[illegible]4.[illegible]	[illegible]6.[illegible]	[illegible]	[illegible]	[illegible]3[illegible]	[illegible].3	116.2
Total	[illegible]	2,[illegible].2	[illegible]	[illegible]	1,[illegible].1	1,[illegible]	[illegible]	[illegible]	[illegible].1	412.0
M. After-tax profit (J-K)	-380.9	[illegible]	1,162.1	2,[illegible].6	3,[illegible]	[illegible]	[illegible]1.6	[illegible]	[illegible]	5,956.5
N. Net earnings (M+L)	-3[illegible]	[illegible]	3,0[illegible].3	[illegible]	[illegible]	[illegible].2	[illegible]1.7	[illegible]	[illegible].9	6,368.6

1/ Data may not equal totals because of rounding and truncating.

is either 0.8638 or 0.8163 times the 1978 values in order to account for a 5 or 7 percent annual compound increase in prices. However, labor cost changed at a different annual rate, and the adjustment for labor is 0.8531 times the 1978 cost. Total expense for sales promotion was averaged for the 10 years to give an average yearly cost for 1975. Straight-line depreciation for a 10-year period was used for computing depreciation cost for 1975. After making these adjustments, the 1975 values were divided by 35,640,000 (the number of studs produced per year) to obtain the cost per stud and by 190,080,000 (the number of board feet produced per year) to obtain the cost per M board feet. Table 16 shows the 1975 estimated manufacturing cost for COM-PLY studs made in Arkansas and selling at $130/M board feet.

Computing the operating cost shown in table 15 is difficult and requires much time for collecting accurate data. Potential manufacturers of COM-PLY studs probably have a good source of data in their own company records. By using their own data and making computations similar to those shown in this section, manufacturers can more accurately estimate the factory cost for their own company.

Table 16.--Estimated manufacturing cost in 1975 for COM-PLY studs made in Arkansas and selling at $130/M board feet f.o.b. at the mill

Item	Cost per stud	Cost per M board feet
	- - - -Dollars- - - - - -	
Raw material		
Logs	0.142	26.70
Particleboard resin	.152	28.50
Resin catalyst	.010	1.80
Wax	.008	1.40
Veneer adhesive	.060	11.20
Labor	.063	11.90
Power and fuel	.030	5.60
Other production expenses	.021	4.00
Administrative expenses	.012	2.30
Sales promotion	.004	.80
Facilities expense	.003	.50
Contingency expense	.014	2.60
Sales expense	.035	6.50
Depreciation	.032	6.00
Total	.586	109.80

NET CASH FLOWS AND INTERNAL RATE OF RETURN

The previous sections dealt with the estimated investment to build a COM-PLY stud factory and the net annual earnings that might be expected from its operation. In one section, we were considering cash outlays for an investment and in the other section we were considering cash proceeds that accrue from profitable operation. Potential manufacturers of COM-PLY studs want to know what return on their investment they can expect from the cash proceeds or net earnings.

The return on investment is found by determining interest rates on the basis of the present-value concept. In simple terms, if we invest $100 today at 6 percent interest, the value 1 year from today is $106. The $106 is called the future sum. The future sum includes the original amount (present value) plus interest accumulated (return on investment). The $100 is analogous to investments or cash outlays to build a factory, while the $106 is analogous to cash proceeds resulting from profitable operation. If we did not know the interest rate for the present value of $100 and future sum of $106 for a period of 1 year, we could find it by using trial interest rates until we found one that yielded $6 per year on a $100 investment.

The process of computing the present value of future sums at a given interest rate is referred to as discounting. In this study, the annual cash outlays (such as for investments) are considered as negative future sums and annual cash proceeds (such as net earnings from profitable operation) are considered as positive future sums. The object of the analysis is to find the compound interest or discount rate for 10 annual periods when the present value (at the beginning of the investment period or time zero) of the cash outlays is just equal to the present value of the cash proceeds. This procedure is widely used for evaluating the economic feasibility of investments and is often referred to as a discounted cash flow analysis. Finding the appropriate compound interest or discount rate is a trial-and-error process.

In finding the appropriate discount rate, a low interest rate is selected and the net annual cash flows (outlays and proceeds) or future sums are converted to their present value on the basis of the rate selected. If the cumulated net annual cash flow is positive, then the present value of the cash proceeds is greater than the present value of the cash outlays for the 10 years of operation. In that case, a higher trial interest rate is selected and the procedure is repeated until a rate is found at which the positive present values of cash proceeds just equal the negative present values of cash outlays. This interest or discount rate is called the internal rate of return. Table 17 shows a discounted cash flow analysis if COM-PLY studs are sold for $130/M board feet.

Table 17.--Discounted cash flows at a 15 percent rate of return for a COM-PLY stud factory during a 10-year investment period[1]

Year	Outlay (investment)		Proceeds (net earnings)		Net annual cash flow		Present value			
							At 15%		Annual return	Cumulative
	Thousands of dollars									
0	-344.7	+	0	=	-344.7	X	1.0000	=	-344.7	-344.7
1	-6,108.2	+	-380.9	=	-6,489.1	X	.8696	=	-5,642.7	-5,987.4
2	-8,843.7	+	969.8	=	-7,873.9	X	.7561	=	-5,953.8	-11,941.2
3	-1,771.5	+	3,016.3	=	1,244.7	X	.6575	=	818.4	-11,122.7
4	0	+	4,225.8	=	4,225.8	X	.5718	=	2,416.1	-8,706.6
5	0	+	4,478.8	=	4,478.8	X	.4972	=	2,226.7	-6,479.9
6	0	+	4,763.2	=	4,763.2	X	.4323	=	2,059.3	-4,420.6
7	0	+	5,081.7	=	5,081.7	X	.3759	=	1,910.4	-2,510.2
8	0	+	5,437.0	=	5,437.0	X	.3269	=	1,777.4	-732.8
9	0	+	5,831.9	=	5,831.9	X	.2843	=	1,657.8	925.0
10	4,642.5	+	6,368.6	=	11,011.1	X	.2472	=	2,721.8	3,646.7

[1] Data may not equal totals because of rounding and truncating.

The first column in table 17 shows the year or period of investment. Year 0 represents the beginning of year 1, but the other numbers--1 through 10--represent year-end times. The next column shows cash outlays for investment and is taken from table 2. The values are negative because they represent cash outlays, except for the value at year 10. This value represents working capital (cash, inventory, accounts receivable) that is recovered at the end of the investment period. The recovered working capital is treated as a positive nontaxable cash flow.

Column 3 is taken from the net earnings (table 15). If production operations are unprofitable, the net earnings will be negative. However, if the production operation is profitable, the net earnings are positive and represent cash proceeds.

Column 4 is the sum of columns 2 and 3 and represents net annual cash flows.

Column 5 lists the present-value factor for a 15 percent interest rate. This interest rate was selected because it represents a minimum rate of return on an investment. At rates of return less than 15 percent, a company might be better off to invest elsewhere. The values in column 4 represent future sums at the end of the year indicated. By multiplying the values in column 4 by the present-value factor in column 5, the amount in column 4 is discounted (moved backward through time) to its present value (shown in column 6). For example, at the end of year 5, the net annual cash flow was $4,478,800 and the present value of annual return was $2,226,700. In other words, if we had invested $2,226,700 at time zero at a compound interest rate of 15 percent, we would have a future sum of $4,478,800 at the end of 5 years.

Column 7 shows the cumulative present values of annual cash flows in column 6. At a discount rate of 15 percent, the $17,068,200 investment would be paid back in 8.44 years. Thus, the internal rate of return is 21.09 percent. In other words, if we had used present-value factors for a discount rate of 21.09 percent, the investment would have been paid back at the end of the tenth year. For a discount rate of 21.09 percent, the negative present values of the cash outlays would just equal the positive present values of the cash proceeds over a 10-year period.

Internal rates of return were calculated for the three price levels of studs, but the operating cash flows and discounted cash flow analysis are shown only for studs priced at $130/M board feet at the mill. Rates of return and related factors for the three price levels are summarized in table 18.

Table 18.--Payback periods, internal rates of return, and break-even points for a COM-PLY factory selling studs at three price levels (f.o.b. mill)

Sales price for studs (Dollars/M board feet)	Payback period at 15 percent discount rate	Internal rate of return for 10-year investment period	Break-even point
	Years	Percent	M board feet
123.50	9.50	17.16	97,086
130.00	8.44	21.09	81,891
136.50	7.44	24.75	71,019

DISCUSSION AND CONCLUSIONS

Under average conditions, a manufacturer should be able to obtain an internal rate of return of 20 percent or more on an investment in a new COM-PLY stud factory. However, much greater profit potential exists if existing facilities for manufacturing particleboard and veneer are converted to the manufacture of COM-PLY studs. For such a conversion, investment would be less and positive annual cash flows would occur sooner than if a new plant were built. For a small investment in a stud-laminating operation, the return on the total investment would be much larger than shown in this study.

Conversion of existing facilities to the manufacture of COM-PLY studs would also help alleviate this country's current excess capacity to produce particleboard. Because so many particleboard plants have been built, many of them are providing a low internal rate of return. A 100 percent conversion from particleboard to COM-PLY studs would not be necessary. Even converting one-third of a factory's particleboard production to COM-PLY studs should greatly improve its earning capacity.

Consumer demand for particleboard often peaks a year or two after the peak demand for lumber and plywood, primarily because demand for lumber and plywood is greatest during a housing boom. After a housing boom subsides, the need for lumber and plywood drops off, as it did late in 1973. Subsequently, construction of shopping centers and manufacture of furniture increase, both of which create a strong demand for particleboard.

There are other financial benefits for a manufacturer who can produce COM-PLY lumber and particleboard in one factory. He can shift production to the product in greatest demand. As a result, a facility that can produce both products has the potential for larger positive cash flows over a longer period of time than one that produces particleboard alone. Under present practice, many particleboard plants suffer heavy losses or are forced out of business during recessions.

Potential manufacturers should carefully compare the manufacturing costs for COM-PLY studs (table 16) with those for sawn lumber studs, especially from the standpoint of fluctuating costs of raw materials. One of the greatest expenses in making conventional studs is the cost of wood. During periods of peak demand for lumber, the prices for stumpage increase, more so for softwoods than hardwoods. Because COM-PLY studs can be made from a mixture of hardwoods and softwoods, they have a distinct cost advantage in raw materials. Furthermore, wood represents a smaller percentage of the total cost of a COM-PLY stud than of a conventional stud. In COM-PLY studs, the cost for resin binder, catalyst, wax, and laminating adhesive is greater than for wood. These nonwood costs do not fluctuate greatly in unison with wood prices.

In the future, we will undoubtedly face the problem of getting 2 x 6's, 2 x 8's, and 2 x 10's for lumber-framing from smaller logs than have been available in the past. This study shows that it is economically feasible to manufacture COM-PLY 2 x 4's now. Therefore, the economic potential for making even larger COM-PLY lumber framing is highly favorable.

This study was made for the investment period from 1975 to 1985. As time passes, manufacturing costs will tend to favor COM-PLY studs over sawn lumber studs. Analysis of financial feasibility for some later period--say 1980 to 1990--should show even greater internal rates of return than those we found for the period from 1975 to 1985.

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The investment and production costs required to manufacture COM-PLY studs in the South are presented. It is possible to obtain a 20 percent or greater internal rate of return on an investment in manufacturing COM-PLY studs.

KEYWORDS: Manufacturing costs, stud cost, economics of stud manufacture, cost analysis, COM-PLY factory, rate of return.

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Stand, Soil, and Site Characteristics Associated with Southern Pine Beetle Infestations in the Southern Appalachians

by
Roger P. Belanger
Eben A. Osgood
Glyndon E. Hatchell

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Southeastern Forest Experiment Station

February 1979

Southeastern Forest Experiment Station
Asheville, North Carolina

Stand, Soil, and Site Characteristics Associated with Southern Pine Beetle Infestations in the Southern Appalachians[1]

by

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Abstract.—Southern pine beetle infestations were studied in the Southern Appalachians during 1957 and 1975–77 to determine stand, soil, and site characteristics associated with beetle attacks. Comparisons are made between representative forest conditions for the study area and the 1975–77 infested plots. Stands severely attacked by the southern pine beetle were characterized by dense stocking, slow radial growth, and a large proportion of overmature pine sawtimber. Shortleaf pine, pitch pine, and loblolly pine were more susceptible to beetle attack than Virginia pine and eastern white pine. Intermediate cutting, favoring more resistant pine species, and favoring mixtures of hardwoods and pines are recommended as a means of reducing losses from the southern pine beetle.

KEYWORDS: *Dendroctonus frontalis* Zimmerman, Southern Appalachians, management, preventive measures.

The southern pine beetle, *Dendroctonus frontalis* Zimmerman (SPB), has been a problem for decades in the Southern Appalachians. Several outbreaks have been reported since 1920 (King 1972; Price and Doggett 1978), the most recent activity having occurred from 1972 through 1977. Although losses have been severe, no guidelines exist for preventing or reducing beetle-caused mortality in the mountains. In 1957 Osgood studied southern pine beetle infestations throughout the Southern Appalachians to evaluate forest conditions related to attack.[2] Infested areas were also studied in the mountains of Georgia from 1975 to 1977 with the same objective (Belanger and others 1976). Findings and conclusions from these investigations were strikingly similar. They identify stands that are highly

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[1] The work herein was funded in part by a U.S. Department of Agriculture sponsored program entitled "The Expanded Southern Pine Beetle Research and Applications Program."

[2] Osgood, E. A. 1958. A study of the site and stand characteristics of southern pine beetle infestations. Unpublished Off. Rep., 5 p. U.S. Dep. Agric. For. Serv., Southeast. For. Exp. Stn., Athens, Ga.

susceptible to beetle attack and provide silvicultural alternatives managers can use to reduce losses from the southern pine beetle.

METHODS

In 1957, stand and site characteristics were surveyed on 46 randomly selected southern pine beetle infested areas in the mountains of North Carolina, South Carolina, Georgia, and Tennessee. The 1975-77 survey included 22 stands infested by the southern pine beetle in the mountains of Georgia. Spot locations were provided by the Georgia Forestry Association, the Chattahoochee-Oconee National Forest, and ground survey teams. All 68 plots were in natural stands and most of the plots were in National Forests. Beetle populations during both study periods were endemic or in decline from epidemic conditions.

Both studies included estimates of basal area, the proportion of pine and hardwoods, site index, age, radial growth, and aspect. Stand density was estimated in 1957 using a 3-diopter prism; a 10-factor prism was used during the 1975-77 study. Age and radial growth were measured from increment borings of three to six dominant and codominant trees per study plot. Both infested and uninfested trees were used to determine growth rates. The 1975-77 study also included forest cover type,[3] the number of SPB-killed trees per infestation, the size of the infested area, and the percent occupation of the lower canopy by woody understory vegetation. Site index was based on shortleaf pine at age 50 (Schumacher and Coile 1960).

Individual tree characteristics recorded during 1975-77 included species, status (alive or SPB killed), d.b.h., total height, height to live crown, and crown class. Minimum and maximum bark thicknesses were measured on the three to six dominant and codominant sample trees.

Soils were inventoried during 1975-77 using the *Soils Resource Guide*, Southern Region (USDA Forest Service 1972). Soil and site characteristics recorded at each study location included landform, source of material, texture, water regime, modifiers (e.g., erosion critical, depth to restrictive layer critical, etc.), percent slope, and depth of the A horizon. Samples collected from the plots were analyzed in the laboratory to determine particle size distribution and pH for surface soil (0- to 6-inch depth) and subsoil (the B horizon).

FINDINGS, 1957 STUDY

Stands infested by the southern pine beetle in the Southern Appalachians during 1957 were characterized by high basal areas and slow diameter growth (table 1). The average total basal area[4] for all plots was 144 ft^2/acre; 78 percent of the infested plots had greater than 100 ft^2/acre. Basal areas on individual plots ranged from 56 to 298 ft^2/acre. Stands with low basal areas were located on poor sites or where stocking had recently been decreased due to logging operations. Poor radial growth was a characteristic of all infested stands. Trees on 41 of the 46 plots averaged less than an inch of radial growth during the 10 years prior to infestation. Radial growth was less than one-tenth inch on all plots the year prior to attack.

Average age of infested stands was 48 years and ranged on individual plots from 23 through 122 years. In most instances growth slowed noticeably when stands reached 30 years of age. Eighty-seven percent of the attacks occurred in stands that were 30 years or older.

Pine represented more than half of the basal area stocking on 40 of the 46 infested plots. Seventy-eight percent of the stands, however, contained some hardwoods.

Attacks occurred from ridge tops to stream bottoms and over a wide range of site indices. Sixty-eight percent of the attacks during 1957 were on south-facing slopes.

THE 1975-77 STUDY

STAND CHARACTERISTICS

The average stand infested by southern pine beetles in the mountains of Georgia during 1975-77 was overmature, heavily stocked, and slow growing (table 2). The average age of infested stands was 62 years and ranged from 35 through 110 years of age. Total basal area averaged 129 ft^2/acre; 18 of the 22 plots had basal areas greater than 100 ft^2/acre.

Pine made up 50 percent or more of the stocking on 95 percent of the plots. Hardwoods were present, however, on 20 of the 22 infested plots. Woody understory vegetation covered an average 67 percent of the area in the lower canopy.

The heavy stocking and dense understory vegetation influenced the growth rate of the pine overstory. Radial growth on dominant and codominant site index trees averaged only 0.66 inch during

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[3] Stands in which a specific type species represents 70 percent or more of the crowns in the dominant and codominant position.

[4] Total basal area based on all pine and hardwood $\geq$ 1-inch d.b.h.

Table 1.–Characteristics of stands infested by the southern pine beetle in the Southern Appalachians during 1957

Location	Plots	Site index	Age	Basal area			Radial growth		
				Pine	Hard-wood	Total	10 Years	5 Years	1 Year
	Number		*Years*	. . . . .	*ft*^{2}		. . . .	*Inch*	
South Carolina	22	65	41	111	32	143	0.753	0.346	0.053
Georgia	8	55	61	100	42	142	.572	.256	.035
Tennessee	9	58	49	126	3	129	.634	.288	.055
North Carolina	7	55	51	144	24	168	.600	.290	.047
Average all plots	–	60	48	117	27	144	.675	.310	.049
Average annual growth	–	–	–	–	–	–	.067	.062	.049

Table 2.–Characteristics of stands infested by the southern pine beetle in the mountains of Georgia during 1975–77

Variable	Average	Range
Basal area:		
Pine (ft^2/acre)	92	30 – 140
Hardwoods	37	0 – 70
Total	129	50 – 180
Density (total stems/acre)	658	49 – 2,603
Site index*	66	50 – 84
Understory (percent)	67	30 – 100
Spot size (acres)	1.4	.2 – 20
SPB-killed trees (number)	43	5 – 300
D.b.h. (inches)	11.7	6.1 – 17.8
Total height (feet)	66	41 – 92
Live crown ratio (percent)	42	31 – 62
Age (years)**	62	35 – 110
Bark thickness, maximum (inch)**	.85	.51 – 1.24
Bark thickness, minimum (inch)**	.50	.33 – .65
Radial growth 0 to 5 years (inch)**	.30	.08 – .51
Radial growth 5 to 10 years (inch)**	.36	.12 – .66

*Based on shortleaf height at 50 years (16 plots).

**Measurements taken on site-index trees.

the last 10 years and 0.30 inch during the last 5 years. Radial growth decreased as d.b.h. and stand age increased. Only 3 of the 22 infested plots were less than 40 years of age. These plots had more radial growth the 10 years prior to infestation (0.9, 1.1, and 1.2 inches) than all the other plots.

Infestations occurred across a wide range of site indices. Regression analyses showed no relationship between size of the infestation or number of trees killed by the southern pine beetle and site index.

More than half of the infested plots occurred in shortleaf pine (*Pinus echinata* Mill.) type (table 3).

Table 3.–Severity of southern pine beetle infestations, by pine type

Pine type	Plots	Size of infestation		Trees killed by SPB	
		Average	Range	Average	Range
	Number	. . . . *Acres*	. . . .	*Number*	
Loblolly	2	0.62	0.25 – 1.00	23	6 – 40
Shortleaf	13	1.88	.25 – 20.00	46	5 – 300
Virginia	2	1.12	.25 – 2.00	42	6 – 79
Pitch	5	.55	.25 – 1.00	43	10 – 100

Other pine types infested were pitch pine (*P. rigida* Mill.), Virginia pine (*P. virginiana* Mill.), and loblolly pine (*P. taeda* L.). There was little difference in number of trees killed per infestation between shortleaf pine, Virginia pine, and pitch pine. The fewest number of trees killed per spot occurred in the loblolly pine type. This species, however, represents only a small and atypical portion of the total pine composition in the mountains of Georgia.

SOIL AND SITE CHARACTERISTICS

Soils on the mountain plots were formed from predominantly mica and mafic parent materials. Laboratory analysis indicated that the average texture of the 0- to 6-inch surface horizon is sandy clay loam and the B horizon is sandy clay (table 4). Average depth of the A horizon was 5.3 inches. Only four plots had layers within 20 inches of the surface that

Table 4.—Soil characteristics of stands infested by the southern pine beetle in the mountains of Georgia during 1975-77

Variable	Average	Range
"A" horizon (surface soil)		
Depth (inches)	5.3	1.2 – 14.2
Sand (percent)	54	31 – 74
Silt (percent)	19	4 – 36
Clay (percent)	27	14 – 57
pH	4.7	4.4 – 5.3
"B" horizon (subsoil)		
Sand (percent)	44	12 – 78
Silt (percent)	19	9 – 33
Clay (percent)	37	13 – 65
pH	5.0	4.6 – 5.4

could have restricted root development. Eighteen of 22 plots were classified as dry (14 plots), droughty (3 plots), or very droughty (1 plot). More infestations fell on south-facing slopes (13 plots) than on north-facing slopes (9 plots).

INDIVIDUAL TREE CHARACTERISTICS

Data were also tabulated on individual tree species (table 5). Species killed by the southern pine beetle were loblolly pine, shortleaf pine, Virginia pine, pitch pine, and eastern white pine (*P. strobus* L.). Individual tree data indicate pitch pine was most susceptible to southern pine beetle attack (92 percent mortality). Pitch pine trees were older, larger, slower growing, and had thicker bark than loblolly pine, shortleaf pine, or Virginia pine. Mortality rates were also high for these species—79 percent, 78 percent, and 79 percent respectively. White pine tended to resist attack with only two out of seven trees killed. The frequently observed ability of white pine to "pitch out" southern pine beetles may account for its low rate of mortality. Such a small data base, however, does not permit firm conclusions.

Trees killed by the southern pine beetle were generally slower growing and smaller in diameter than trees that survived or escaped attack. However, t-tests indicated no significant differences between live and SPB-killed trees for any of the variables listed.

A COMPARISON OF INFESTED PLOT DATA AND BASELINE DATA

Forest Service inventory statistics were used as baseline data to characterize representative forest types and conditions with the 1975-77 southern pine

Table 5.—Characteristics of live and southern pine beetle killed trees on infested plots

Species	Trees			Age		D.b.h.		Height		Radial growth				Bark thickness			
										0 to 5 years		5 to 10 years		Maximum		Minimum	
	Alive	SPB dead	Mortality	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead
	Number		*Percent*	*Years*		*Inches*		*Feet*		. . . . *Inch*				. . . . *Inch*			
Loblolly pine	3	11	79	65	58	12.7	10.1	53	52	0.55	0.41	0.63	0.46	0.9	0.9	0.6	0.6
Shortleaf pine	26	91	78	57	62	11.1	10.5	67	67	.34	.27	.39	.35	.8	.8	.5	.5
Virginia pine	6	22	79	61	44	10.0	11.3	64	65	.67	.39	.31	.44	.3	.6	.2	.3
Pitch pine	3	33	92	73	69	14.8	12.0	65	62	.26	.26	.35	.30	1.1	1.0	.6	.6
Eastern white pine	5	2	29	55	67	12.5	24.3	65	94	.75	.22	.75	.24	.9	.7	.6	.3

beetle survey.[5] Baseline and infested plot data were from the same five mountain counties in Georgia. Resource information (table 6) shows that the predominant pine type is Virginia pine, yet only 9 percent of the 1975-77 infestations fell in the Virginia pine type. Although 10 percent of the forest land was typed as white pine, no SPB were established in the white pine timber type. Fifty-nine percent of the infestations occurred in the shortleaf pine type, which represented only 29 percent of the area in pine, again indicating that shortleaf pine is highly susceptible to SPB attack. Comparisons between infested plot data and baseline data indicate that the pitch pine and loblolly pine types are also susceptible to attack in the mountains.

Table 6.–Distribution of pine species on plots infested in 1975-77 and on Forest Survey plots classed as pine in the mountains of Georgia

Source	Shortleaf	Virginia	Pitch	Eastern white	Loblolly
			Percent		
Infested	59	9	23	–	9
Forest Survey	29	55	6	10	–

Resource data indicate infestations occur in stands with more basal area than is characteristic of the mountains (table 7). Total basal area of infested plots averaged 129 ft²/acre, as compared to 103 ft²/acre for survey plots. Infestations were more prevalent in pine stands than in pine and hardwood stands. Ninety-five percent of the 1975-77 infestations occurred in stands typed as pine, whereas Forest Survey classified only 60 percent of the host type in the area as pine. Infested plots also contained larger and older trees than did baseline plots. Overmature dense pine stands are high-hazard southern pine beetle areas in the mountains of Georgia.

Table 7.–Average stand characteristics on plots infested in 1975-77 and on Forest Survey plots classed as pine in the mountains of Georgia

Source	Basal area			Age[1]	D.b.h.[1]	Total height[1]
	Pine	Hardwood	Total			
		ft²/acre		*Years*	*Inches*	*Feet*
Infested	92	37	129	63	11.3	63
Forest Survey	76	27	103	33	9.5	54

[1] Based on trees 5 inches d.b.h. and larger.

DISCUSSION

Stands attacked and killed by the southern pine beetle during the 1957 and 1975-77 infestations were characterized by dense stocking, slow radial growth, and overmature predominantly pine species. Infestations did occur in stands that had low total basal-area stocking or where pine represented a small component of the total basal area; however, mature and slow-growing trees were also characteristic of these stands.

No significant differences existed between live trees and trees killed by southern pine beetle for age, size, or growth variables measured during the 1975-77 infestations. This indicates successful insect attack in the mountains may be more related to stand conditions than individual tree characteristics.

Contrary to common belief, infestations did not occur primarily on ridge tops or on shallow soils underlain by bedrock. There was no relationship between infestations and position on the slope. Only four plots had layers within 20 inches of the surface that could have restricted root development.

Fifty-nine percent of the infestations were recorded on south-facing slopes, compared to 41 percent on north-facing slopes. The higher percentage of infestations on south-facing slopes is to be expected, because this is where most of the pines occur in the Southern Appalachians.

All 1975-77 plots were revisited in late summer 1977. Salvage cuts of merchantable pine had been made on 7 of the 22 plots. The hardwood overstory and understory had already responded to release from cutting and southern pine beetle attack (fig. 1). Hardwoods will form the basis of future stands.

Conditions that lead to successful southern pine beetle attacks in the mountains are different from those that exist in other physiographic regions of the Southeast. Whereas infestations in the mountains are related to stand conditions, high-hazard areas in the piedmont of Georgia are primarily associated with soil conditions (Belanger and others 1976). Southern pine beetle infestations in the coastal plain of North Carolina appear related to a combination of soil and stand characteristics. Guidelines to reduce losses of southern pines to beetle attacks should be specific to particular regions.

Another point deserves mention: Both the 1957

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[5] Information supplied by Renewable Resources Evaluation, USDA For. Serv., Asheville, N. C. Data collected July-September 1972.

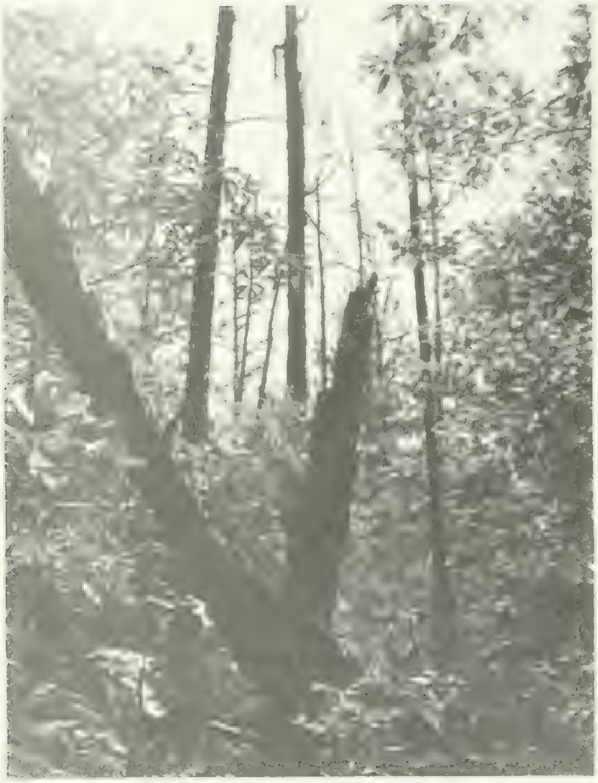

Figure 1.–Hardwoods have replaced pine on many areas infested by the southern pine beetle in the Southern Appalachians.

and the 1975-77 surveys were made when southern pine beetle populations were endemic or in decline from epidemic conditions. Stand, site, and weather conditions that favor attack and spread during these periods may be quite different from those that influence infestations when beetle populations are increasing or epidemic (Moore and Thatcher 1973).

MANAGEMENT AND SILVICULTURAL IMPLICATIONS

These studies indicate that management and silvicultural techniques offer means of reducing pine mortality from the southern pine beetle in the Southern Appalachians. Preventive measures may differ, depending on management objectives and value of the stand.

A combination of thinning, improvement cuts, and salvage cuts may be used to reduce the basal area of overstocked stands. Approximately 80 to 90 ft^2/acre of leave basal area is recommended for these types of stands (USDA Forest Service n.d.). Overmature, slow-growing trees should be cut to improve the age distribution and growth potential of the residual stand. It may be necessary to carry out two or three intermediate cuts to obtain the desired results.

Managing species composition deserves consideration as a method of reducing losses from southern pine beetle. The 1975-77 study showed that shortleaf pine, pitch pine, and loblolly pine were highly susceptible to southern pine beetle attack. Size of infestation and number of trees killed per plot were greatest in the shortleaf pine type. Managers should favor eastern white pine and Virginia pine when possible.

Another preventive measure is managing pine and hardwoods in mixture. Hardwoods are a component of most pine stands and the climax species in the mountains. Favoring hardwoods during intermediate cutting will reduce the incidence of beetle attack as well as improve the quality of stands and site.

Silvicultural prescriptions will not eliminate losses from the southern pine beetle. The variation, dynamics, and unknowns of insect behavior and forest stands preclude this idealistic goal. The land manager also has to consider stumpage values, market conditions, and the accessibility of stands when prescribing and scheduling cultural treatments. Primary emphasis should be given to high-risk stands within areas that contribute significantly to management objectives. Fast-growing stands should be thinned to recommended basal areas and harvested before stands reach old age. Host management provides the opportunity to reduce the probability of southern pine beetle infestations and to minimize losses should outbreaks occur.

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Southern Appalachian stands severely attacked by the southern pine beetle were characterized by dense stocking, slow radial growth, and a large proportion of overmature pine sawtimber. Shortleaf pine, pitch pine, and loblolly pine were more susceptible to beetle attack than Virginia pine and eastern white pine. Intermediate cutting, favoring more resistant pine species, and favoring mixtures of hardwoods and pines are recommended as means of reducing losses from the southern pine beetle.

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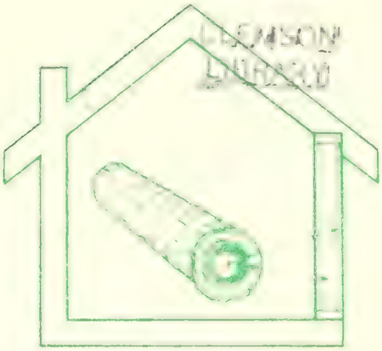

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COM-PLY® 16 REPORT

STRUCTURAL PERFORMANCE OF COM-PLY STUDS MADE WITH HARDWOOD VENEERS

COOPERATIVE RESEARCH

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June 1979

Southeastern Forest Experiment Station
Asheville, North Carolina

STRUCTURAL PERFORMANCE OF COM-PLY STUDS MADE WITH HARDWOOD VENEERS

by

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Cooperative Research by
U.S. Department of Agriculture, Forest Service
Southeastern Forest Experiment Station
and
U.S. Department of Housing and Urban Development
Division of Energy, Building Technology
and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing was initially limited to COM-PLY studs but has now been extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The Forest Service of the U.S. Department of Agriculture and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of COM-PLY studs and joists is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall and floor framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs and joists. Other reports will describe the overall project, compare the strength of composite and solid wood lumber, suggest performance standards for composite lumber, and provide construction details on houses incorporating such lumber. Still others will explore the economic feasibility of manufacturing composite lumber and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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STRUCTURAL PERFORMANCE OF COM-PLY STUDS MADE WITH HARDWOOD VENEERS

ABSTRACT.—COM-PLY 2 x 4 studs made with veneers of yellow-poplar, sweetgum, and white oak were tested for strength and stiffness, nail-holding properties, modulus of elasticity of component parts, static bending, and compression parallel and perpendicular to the grain. All tests were conducted according to performance standards for composite studs used in exterior walls or ASTM standards. Results indicated that the tested properties of COM-PLY 2 × 4's with any of the three hardwood veneers are comparable to those of COM-PLY 2 × 4's with southern pine veneers and to 2 × 4's of solid wood.

KEYWORDS: Modulus of elasticity, strength, stiffness, bending,compression, nail-holding ability, veneer, particleboard.

The Forest Service, U.S. Department of Agriculture, the Department of Housing and Urban Development, and several manufacturers of forest products have cooperated in developing a new composite lumber product. This product, the COM-PLY stud, is a structural sandwich with a particleboard core placed between layers of solid wood veneer.

The major use of forest products is in residential and commercial construction. Almost all of the wood products used in construction are softwoods. This dependence on softwoods is based on their availability, ease of drying and nailing, and generally lighter weight in comparison with hardwoods. Projections indicate that the future demand for softwood products will exceed supply.

Forested land in the United States is predominantly in hardwoods. If future demands for forest products are to be satisfied, methods must be found to use more of our hardwood resource. Select hardwood lumber and veneer have always had a ready market for use in furniture, cabinets, and paneling. For centuries, the hardwood forests have been selectively cut—the high-value trees have been taken and the culls and less desirable species have been left. Consequently, the residual hardwood stands would require more money to harvest and prepare for restocking than would accrue from selling the harvested timber for conventional processing.

The COM-PLY approach to manufacturing composite lumber and panels is ideally suited to the efficient use of hardwood stands. Composite products reduce or eliminate the major problems with hardwood utilization—long drying times, poor dimensional stability, and the difficulty of obtaining large sizes and long lengths of lumber. Since 60 to 80 percent of a COM-PLY product consists of the particleboard core, such products can utilize low-quality forest or manufacturing residues.

There is an abundant supply of several species of hardwoods that are not being used. Consequently, potential manufacturers and users of COM-PLY studs need to know about the structural performance of COM-PLY studs made with hardwood veneers. COM-PLY studs might be used for blocking, posts, headers, beams, or plates. Engineers and building code officials need to know whether COM-PLY studs made from hardwood veneers have sufficient structural strength for these uses.

The strength properties of greatest interest are (1) suitability for use as studs as measured by a performance test of strength and stiffness; (2) working stresses for extreme fiber in bending as measured by a static bending test; (3) axial load-bearing capacity, or strength in compression parallel to the grain; (4) bearing, or strength in compression perpendicular to the grain of the face plies; and (5) nail-holding ability.

This report, directed principally to designers and engineers, describes how the above strength and mechanical properties were determined for COM-PLY studs made with three species of hardwood veneers. This report is closely related to COM-PLY Report 12, "Structural Properties of COM-PLY Studs," which discusses the characteristics of COM-PLY studs made with softwood veneers (McAlister 1978).

MATERIALS

Yellow-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), and white oak (*Quercus alba* L.) make up over 50 percent of the volume of hardwood stands in the Piedmont of the Southeastern United States. We selected these three species for testing as the veneer components of COM-PLY studs.

The test studs were fabricated with 1/6-inch-thick veneers which were available from a veneer grade-yield study. Performance standards for composite studs (Blomquist and others 1976) specify that a sample of 10 studs be used to test performance. We decided on the basis of previous tests that a sample of five studs would be sufficient to determine structural properties. Thus, for our series of tests, 15 COM-PLY studs were needed for each hardwood species, or 45 COM-PLY studs in all.

To relate modulus of elasticity (MOE) of the stud components to the physical properties of the assembled COM-PLY studs, we had to determine the MOE of the components before the studs were fabricated. We randomly selected 64 strips of veneer of each species to represent all veneer cut from tree diameter classes of 12 to 20 inches. All strips were 1.5 inches wide, 96 inches long, and nominally 1/6 inch thick. All of the veneer had been conditioned to equilibrium moisture content at 70°F and 40 percent relative humidity.

We used the stress-wave method of determining dynamic modulus of elasticity (MOE_d) for each strip. This method has been described by Koch and Woodson (1968).

The veneer strips were then laminated together into pairs with a phenol-resorcinol adhesive according to the procedures of Vick (1977). The strips were laminated together in predetermined order (strip 1 to strip 2, . . . strip 63 to strip 64) so that the MOE of each component strip was known. After laminating, the MOE_d of each laminate was determined by the stress-wave technique.

The core material used in this study was a phenolic-bonded particleboard 1½ inches thick. The particleboard had an average density of 40 lb/ft^3, an internal bond of 75 lb/in^2, an MOE (in plane of panel) of 300,000 lb/in^2, and contained 8 percent phenolic resin binder throughout the three layers.

Cores for COM-PLY studs were ripped to a width of 2.83 inches. We determined the MOE of the core as a beam 1.5 inches wide and 2.83 inches deep by center-loading as a simple beam over a span of 90 inches. Deflections at midspan were measured to the nearest 0.001 inch for loads of 10, 20, and 30 pounds. We used a dial gage mounted on a yoke to measure the deflections. To calculate the MOE in bending (MOE_b), we subtracted the deflection at 10 pounds of load from the deflection at 30 pounds of load and determined the slope of the load/deflection curve for this 20-pound increment. The MOE_d of the veneer strips and the MOE_b of the particleboard core were used in all calculations.

The two-ply strips were laminated to the cores with the odd-numbered strips to the outside of the assembled stud. Thus, the position of each ply in each stud was known. The gluing procedures used in fabricating the COM-PLY studs had proved satisfactory in previous studies (Vick 1977).

After fabrication, 10 studs from each species group were selected at random for the performance testing. The remaining five studs were cut into segments for the strength tests, as shown in figure 1.

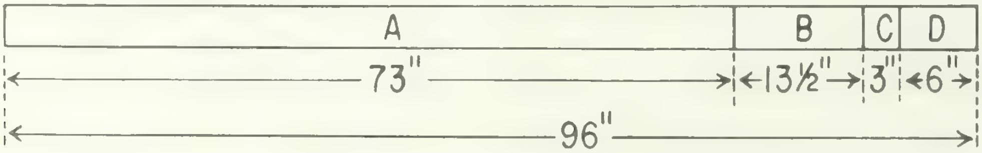

Figure 1.—Location of stud segments for the three strength tests: A, static bending; B, compression parallel to the grain; C, not used; D, compression perpendicular to the grain.

Properties of transformed sections were calculated for all studs according to the method found satisfactory in a previous study (McAlister 1978). Transformed sections were used to calculate all allowable strength properties except static bending.

PERFORMANCE TESTS

METHODS

We conducted the performance tests according to the procedures outlined in "Performance Standards for Composite Studs Used in Exterior Walls" (Blomquist and others 1976). In addition to the combined axial and transverse loading specified, all studs were first tested on edge in static bending under limited load. We used quarter-point loading over a 90-inch span to a maximum load of 250 pounds to determine the bending stiffness factor or EI. To calculate the EI of the COM-PLY studs, we subtracted the deflection under 100 pounds of load from the deflection at 200 pounds of load and calculated the slope of the load/deflection curve for the resulting 100-pound load increment.

RESULTS

The results of the performance tests and the static bending tests under limited load for COM-PLY studs made from yellow-poplar, sweetgum, and white oak veneer are shown in table 1.

The predicted EI was higher than the actual EI for the yellow-poplar and sweetgum studs and lower than the actual EI for the white oak studs. The predicted EI values averaged within 7 percent of the actual EI values. Somewhat closer predictions could be made if the dynamic MOE of the veneers were corrected to tensile MOE. Note that the transformed moment of inertia, I_t, is a little more than half the geometric I of a 1.5-inch-wide by 3.5-inch-deep beam section.

The performance standards for composite studs (Blomquist and others 1976) specify test methods and the methods of calculating allowable loads and allowable deflection. Applying these procedures to the average deflections and maximum loads given in table 1 yields the results shown in table 2. COM-PLY studs with veneers of yellow-poplar, sweetgum, and white oak met the performance criteria. The values are comparable to the performance values of COM-PLY studs made with southern pine veneers.

We plotted load/deflection curves for each of the studs for the static bending and the combined loading tests (axial load of 1,190 pounds plus bending load). A typical plot of the two curves is shown in figure 2. Note that axial loading increases the stiffness of the COM-PLY studs because of the reaction moment at the fixed reaction block in this test.

STATIC BENDING

METHODS

We performed structural static bending tests according to the methods outlined in ASTM D 198-76 (ASTM 1978c). The test span was 69 inches with loads applied at one-third points by a universal testing machine. Head speed was maintained at 0.25 inch per minute. Height and width of the test segments were recorded to the nearest 0.001 inch. Deflections under load were determined by using a dial gage mounted on a yoke, and readings were taken to the nearest 0.001 inch at 100-pound load increments until the deflection was at least 0.500 inch. The gage and yoke were removed and the test was continued until failure. We recorded the time required to load the specimen to failure, the method of failure, and the maximum load.

We calculated the bending stiffness, EI_b, of the COM-PLY studs by subtracting the deflection at 100 pounds of load from the deflection at 300 pounds of load and determining the slope of the load/deflection curve for the resulting 200-pound increment.

RESULTS

The results of the structural static bending tests for the COM-PLY studs made with the three species of hardwood veneers are shown in table 3. The transformed moment of inertia (I_t) for the COM-PLY studs

Table 1.—Component MOE values, stiffness factors, and performance test results for COM-PLY studs made with three species of hardwood veneers

Veneer species	Stud No.	Component MOE			Transformed moment of inertia (I_t)	Bending stiffness (EI)		Performance values		
		Core MOE_b	Average strip MOE_d	Average laminate MOE_d		Predicted	Actual static bending	Deflection at 225 lb	Ultimate load	Ultimate load per foot of span (w)
			. . . . . . *Million lb/in²*		*In⁴*	*Million lb/in²*		*In*	*Lb*	*Lb/ft*
White oak	3	0.284	1.82	1.84	2.97	5.41	5.71	0.348	1,040	138.7
	4	.284	1.82	1.84	2.97	5.41	6.74	.232	1,340	178.7
	6	.285	1.98	2.09	2.93	5.80	5.93	.297	930	124.0
	7	.290	2.01	1.95	2.93	5.89	6.37	.268	1,210	161.3
	8	.259	2.26	2.28	2.85	6.44	6.74	.235	1,200	160.0
	9	.276	2.16	2.14	2.88	6.22	5.93	.314	1,000	133.3
	10	.281	2.10	2.11	2.91	6.11	6.41	.302	975	130.0
	11	.296	2.30	2.20	2.89	6.65	6.96	.298	1,310	174.7
	12	.290	2.07	2.16	2.91	6.02	6.61	.300	1,035	138.0
	14	.281	2.51	2.49	2.84	7.13	7.91	.248	1,150	153.3
	Avg.				2.91	6.11	6.53	.284	1,119	149.2
	SD					.0537	.6339	.0374	143.39	19.13
Yellow-poplar	16	.248	1.90	1.84	2.90	5.51	5.61	.385	800	106.7
	17	.274	1.98	1.99	2.92	5.78	5.35	.303	946	126.1
	18	.255	1.94	1.99	2.90	5.63	5.47	.376	824	109.9
	19	.294	2.22	2.14	2.90	6.44	6.29	.288	1,152	153.6
	20	.276	1.71	1.61	2.98	5.10	4.33	.436	560	74.7
	21	.307	1.94	1.87	2.97	5.76	5.74	.330	981	130.8
	22	.281	1.87	1.75	2.95	5.52	5.41	.337	912	121.6
	23	.272	2.18	2.06	2.88	6.28	5.74	.355	884	117.9
	25	.299	2.04	1.92	2.94	6.00	5.02	.342	885	118.0
	26	.289	2.01	1.90	2.93	5.89	5.27	.372	829	110.5
	Avg.				2.92	5.79	5.42	.352	877	116.98
	SD					.3908	.5138	.0427	150.58	20.07

Table 1.—Component MOE values, stiffness factors, and performance test results for COM-PLY studs made with three species of hardwood veneers–continued

Veneer species	Stud No.	Component MOE			Transformed moment of inertia (I_t)	Bending stiffness (EI)		Performance values		
		Core MOE_b	Average strip MOE_d	Average laminate MOE_d		Predicted	Actual static bending	Deflection at 225 lb	Ultimate load	Ultimate load per foot of span (w)
		..... *Million lb/in²*			*In⁴*	*Million lb/in²*		*In*	*Lb*	*Lb/ft*
Sweetgum	31	.298	1.76	1.70	3.01	5.30	5.07	.350	988	131.7
	32	.302	1.90	1.92	2.98	5.66	5.19	.350	973	129.7
	33	.285	1.86	1.79	2.96	5.51	5.17	.335	990	132.0
	34	.282	1.52	1.48	3.05	4.64	4.77	.354	912	121.6
	35	.252	1.72	1.66	2.94	5.06	4.72	.370	898	119.7
	36	.268	1.70	1.88	2.97	5.05	4.83	.397	835	111.3
	37	.255	1.83	1.82	2.92	5.34	5.17	.347	903	120.4
	39	.252	1.95	1.93	2.89	5.64	5.71	.308	910	121.3
	43	.306	1.82	1.78	3.00	5.46	5.25	.330	983	131.1
	45	.322	1.85	1.92	3.02	5.59	5.55	.310	956	127.5
	Avg.				2.98	5.32	5.14	.345	935	124.6
	SD					.3255	.3203	.0266	51.17	6.83

Table 2.—Summary of performance values for COM-PLY studs made with three species of hardwood veneers

Veneer species	Adjusted load (W*)	Adjusted midspan deflection (D**)
	Lb/ft	*In*
Yellow-poplar	44.6	0.377
Sweetgum	70.3	.360
White oak	67	.306

*W must be greater than 40 to pass performance standard.

**D must be less than 0.412 to pass performance standard.

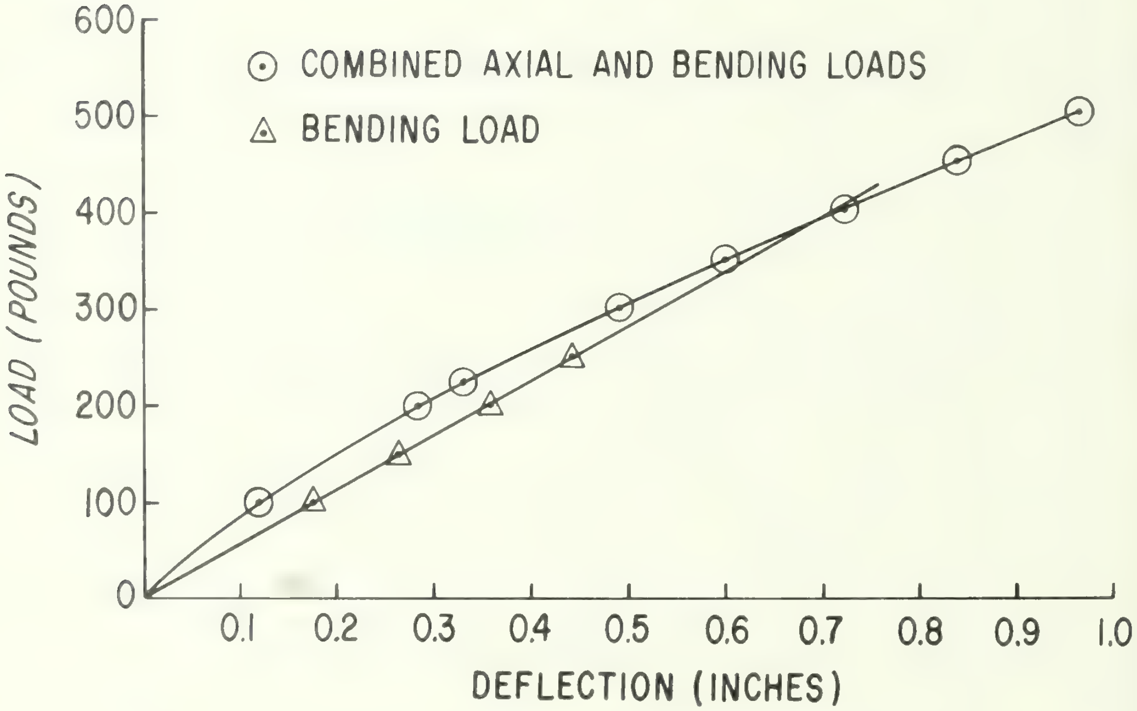

Figure 2.—Typical load/deflection curves for two methods of loading COM-PLY studs.

Table 3.—Results of structural static bending tests on COM-PLY studs made with three species of hardwood veneer as based on transformed section analysis

Veneer species	Stud No.	Average veneer MOE_d	Core MOE_b	Properties of transformed sections			Bending stiffness (EI)		Ultimate load	Maximum moment	Maximum fiber stress (MOR†)
				Moment of inertia* (I_t)	Section modulus (S_t)	Area (A_t)	Actual (EI_b)	Predicted** $(EI_b)_p$			
		Million lb/in²		*In⁴*	*In³*	*In²*	*Million lb/in²*		*Lb*	*In-lb*	*Lb/in²*
White oak	1	2.02	0.280	3.33	1.49	1.72	6.37	6.73	1,653	19,010	5,871
	2	2.19	.311	3.48	1.55	1.78	6.66	7.62	1,675	19,262	5,870
	5	2.65	.301	3.30	1.46	1.63	5.89	8.74	1,470	16,905	5,132
	13	2.27	.283	3.38	1.50	1.69	6.78	7.67	1,375	15,812	4,825
	15	2.04	.237	3.20	1.42	1.61	5.95	6.53	1,450	16,675	5,207
	Avg.	2.23	.282	3.34	1.49	1.69	6.33	7.46	1,525	17.533	5,381
	SD	.255	.028	.101	.047	.069	.404	.881	132	1.522	469
Yellow-poplar	24	2.03	.285	3.19	1.44	1.68	5.45	6.48	1,365	15,698	4,970
	27	1.74	.274	3.17	1.45	1.73	5.35	5.52	1,160	13,340	4,229
	28	2.17	.285	3.26	1.46	1.68	6.41	7.07	1,560	17,940	5,564
	29	2.05	.319	3.34	1.52	1.78	5.50	6.85	845	9,718	3,017
	30	1.83	.276	3.44	1.55	1.80	5.14	6.29	1,285	14,778	4,481
	Avg.	1.96	.289	3.28	1.48	1.74	5.57	6.44	1,243	14,295	4,452
	SD	.175	.018	.113	.046	.057	.489	.599	266	3,056	950
Sweetgum	38	1.96	.252	3.12	1.41	1.63	5.14	6.12	990	11,385	3,537
	40	1.87	.258	3.14	1.42	1.66	4.96	5.87	1,215	13,972	4,427
	41	1.67	.312	3.33	1.54	1.88	4.88	5.56	1,160	13,340	4,218
	42	1.70	.319	3.30	1.53	1.88	4.48	5.61	875	10,062	3,165
	44	1.91	.316	3.20	1.47	1.77	5.03	6.11	1,245	14,318	4,508
	Avg.	1.82	.291	3.22	1.47	1.76	4.90	5.85	1,097	12,615	3,971
	SD	.129	.033	.091	.059	.118	.249	.266	158	1,823	591

*Transformed to average veneer MOE_d base.

**$(EI_b)_p$ = (Average veneer MOE_d) x (I_t).

†MOR calculated by using section modulus for 1.5-inch x 3.5-inch section.

averaged between 3.22 in^4 and 3.43 in^4. These values are somewhat greater than the 2.75 in^4 value found for COM-PLY studs made from slash pine veneer. Part of the difference is due to the generally lower MOE$_d$ of the hardwood veneers in comparison with that of slash pine and also to the slightly greater depth (0.067 inch) of the studs made with the hardwood veneers.

The best predictor of actual bending stiffness (EI$_b$) for the COM-PLY studs was the average MOE$_d$ of the four plies of veneer. There were species differences in the linear regression equations, as follows (all moduli in million lb/in^2):

Veneer species	Regression	Coefficient of determination
		r^2
Yellow-poplar	EI$_b$ = 1.299 + 2.175 × (average veneer MOE$_d$)	0.61
Sweetgum	EI$_b$ = 2.135 + 1.516 × (average veneer MOE$_d$)	.62
White oak	EI$_b$ = 7.330 − 0.447 × (average veneer MOE$_d$)	.08
Slash pine	EI$_b$ = 2.43 + 1.53 × (average veneer MOE$_d$)	.74

The regressions for yellow-poplar and sweetgum are quite similar, but there appears to be no linear relationship for the studs made from white oak veneers. The significant result is that the bending stiffness of COM-PLY studs made from yellow-poplar and sweetgum can be predicted with a good degree of accuracy.

There was little linear correlation between modulus of rupture (MOR) and average veneer MOE$_d$ for COM-PLY studs made from hardwood veneers. This lack of correlation was surprising because there was a close correlation ($r^2 = 0.73$) found for this relationship in COM-PLY studs made from slash pine veneer.

The allowable bending stress based on rectangular section modulus and safe resisting moment in bending were calculated by a formula proposed in ASTM D 245-74 (ASTM 1978a):

$$\text{Allowable strength property} = \frac{\text{Average ultimate strength} - t_{0.05}\,(\text{SD, standard deviation})}{2.1}$$

where $t_{0.05} = 2.132$ for 4 degrees of freedom. A more conservative approach to establishing allowable stresses can be found in ASTM D 2915-74 (ASTM 1978b). The allowable stresses presented below apply only to COM-PLY studs made from materials with properties similar to those used in this study:

Veneer species	Average EI	Allowable fiber stress	Safe resisting moment
	.... *Lb/in*^{2}		*In/lb*
Yellow-poplar	5.57 × 10^6	1,156	3,704
Sweetgum	4.90 × 10^6	1,291	4,156
White oak	6.33 × 10^6	2,086	6,804

A larger sample would tend to increase these allowable design values for COM-PLY studs made with hardwood veneers by decreasing the $t_{0.05}$ value and standard deviation.

The COM-PLY studs made from yellow-poplar and sweetgum have about half the allowable fiber stress value found for COM-PLY studs made from slash pine veneer. However, the values for studs made from yellow-poplar and sweetgum are higher than the 850 lb/in^2 allowable for stud-grade, kiln-dried studs of southern pine (NFPA 1977a).

TESTS OF COMPRESSION PARALLEL TO GRAIN

METHODS

A strength property of interest to engineers and designers is compression strength parallel to the long axis of the stud. Axial loading simulates the use of the stud as a column carrying compressive loads.

The procedure we used to test compression parallel to the veneer grain was based on the recommendation in ASTM D 198-76 (ASTM 1978c). Load was applied through a spherical loading head on a universal testing machine. We recorded deflections over a 6-inch gage length (to the nearest 0.0001 inch) for each 1,000-pound load increment until the COM-PLY column failed.

The load/deflection curve for each COM-PLY column was plotted so that the load at the proportional limit could be determined. A typical load/deflection curve is shown in figure 3. For each column we recorded ultimate load, the time needed to apply that load, and the weight of the section. All dimensions were measured and recorded to the nearest 0.001 inch.

RESULTS

The results of the compressive-load tests are shown in table 4. The average compressive strength (ultimate stress) for the short columns made from COM-PLY studs varied according to wood species, with

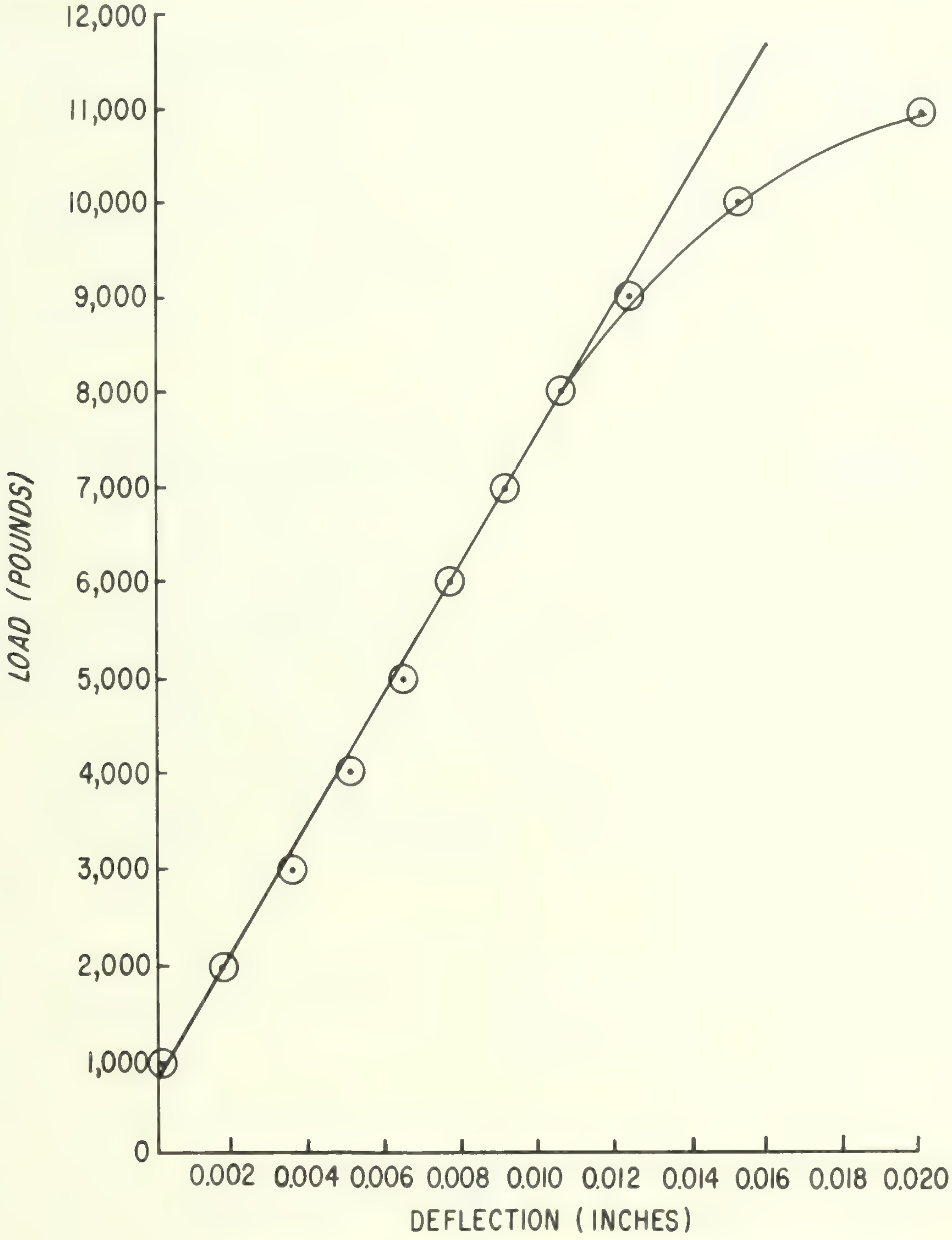

Figure 3.—Typical load/deflection curve for compression parallel to grain of COM-PLY studs made with hardwood veneers.

Table 4.—Values of compressive-load strength and stiffness for COM-PLY studs made with hardwood veneers as based on transformed areas

Veneer species		Stud No.	Load to proportional limit	Ultimate load	Stress at proportional limit	Ultimate stress	Transformed area (A_t)	Compressive MOE
			.... *Lb*	....	..... *Lb/in²*	.....	*In²*	*Million lb/in²*
White oak		1	9,000	12,440	5,223	7,233	1.72	3.48
		2	11,000	14,540	6,183	8,168	1.78	4.82
		5	8,000	13,140	4,897	8,061	1.63	3.34
		13	6,000	14,000	3,545	8,284	1.69	3.54
		15	7,000	11,280	4,357	7,006	1.61	2.49
	Avg.		8,200	13,080	4,841	7,750	1.67	3.53
	SD		1,924	1,288	983	587	.069	.834
Yellow-poplar		24	9,000	13,040	5,351	7,762	1.68	4.46
		27	8,000	11,840	4,613	6,844	1.73	3.14
		28	9,000	12,740	5,367	7,583	1.68	2.98
		29	9,000	14,040	5,045	7,888	1.78	4.80
		30	9,000	12,300	4,996	6,833	1.80	2.56
	Avg.		8,800	12,792	5,074	7,382	1.74	3.59
	SD		447	832	309	508	.057	.982
Sweetgum		38	7,000	11,300	4,299	6,932	1.63	3.68
		40	7,000	11,520	4,217	6,940	1.66	2.41
		41	8,000	12,560	4,252	6,681	1.88	2.28
		42	8,000	12,860	4,261	6,840	1.88	2.66
		44	8,000	12,120	4,511	6,847	1.77	3.08
	Avg.		7,600	12,072	4,308	6,848	1.76	2.82
	SD		548	664	117	104	.118	.570

white oak being the strongest and sweetgum the weakest.

The allowable compressive stresses (f_c) based on transformed section area for COM-PLY studs made with the three species of hardwood veneer, as calculated by the same basic formula (ASTM 1978a) used for bending stresses, were as follows:

Veneer species	Average compressive ultimate stress	Allowable compressive stress
	.... *Lb/in²*	....
Yellow-poplar	7,382	2,999
Sweetgum	6,848	3,155
White oak	7,750	3,094

The f_c values for COM-PLY studs made with the three species of hardwood veneer compare favorably with the allowable f_c of 3,432 lb/in² found for COM-PLY studs made with slash pine veneers and with the allowable f_c of 675 lb/in² for stud-grade, kiln-dried 2 × 4's of southern pine (NFPA 1977a).

The compressive MOE's based on transformed section areas of the COM-PLY studs made with hardwood veneers were quite high, with yellow-poplar and white oak studs averaging over 3.5 million lb/in² and sweetgum studs averaging over 2.8 million lb/in² (table 4).

Surprisingly, there was no correlation found between the compressive MOE and the bending stiffness and modulus of rupture for COM-PLY studs made with hardwood veneers. Reasonably good correlations for these relationships were found for COM-PLY studs made with slash pine veneers.

TESTS OF COMPRESSION PERPENDICULAR TO GRAIN

METHODS

The test for compression perpendicular to the veneer grain measures a stud's ability to resist crushing or bearing loads. Our test of this property was based on the procedures outlined in ASTM D 143-52 (ASTM 1978d). Only the 1½-inch-wide veneer edge was tested because the veneer plies in the 3½-inch face were not perfectly aligned with the core. Removing enough core and veneer material to provide flat, parallel surfaces would have caused erroneous test results.

The tests were made on a universal testing machine with a capacity of 10,000 pounds. Head speed was 0.01 inch per minute. We measured the deflection of the 2-inch-wide loading block (to the nearest 0.0001 inch) for each 200-pound load increment until the total deflection reached 0.10 inch. We considered that the 0.10-inch deflection constituted failure. This load was recorded as the maximum load.

The load/deflection curve was plotted so that the load at the proportional limit could be determined. A typical load/deflection curve is shown in figure 4. For each test segment we recorded the weight, all dimensions to the nearest 0.001 inch, the identification number of the outer veneer ply under the loading block, and the time required to reach a deflection of 0.10 inch.

RESULTS

Results of these tests are shown in table 5. The average fiber stress at proportional limit for all species was considerably higher than for COM-PLY studs made from slash pine veneer. The allowable bearing stresses calculated by the same basic formula (ASTM 1978a) would be:

$$\begin{array}{c}\text{Allowable}\\ \text{bearing}\\ \text{stress}\end{array} = \frac{\text{Average stress at proportional limit} - t_{0.05}\,(\text{SD})}{1.5}$$

Such calculations would yield the following results for COM-PLY studs made with the three species of hardwood veneer:

Veneer species	Allowable bearing stress
	Lb/in²
Yellow-poplar	432
Sweetgum	547
White oak	601

These allowable stresses in bearing are greater than the 405 lb/in² allowable (NFPA 1977a) for stud-grade, kiln-dried 2 × 4's of southern pine and the 227 lb/in² allowable for COM-PLY studs made with slash pine veneers (McAlister 1978).

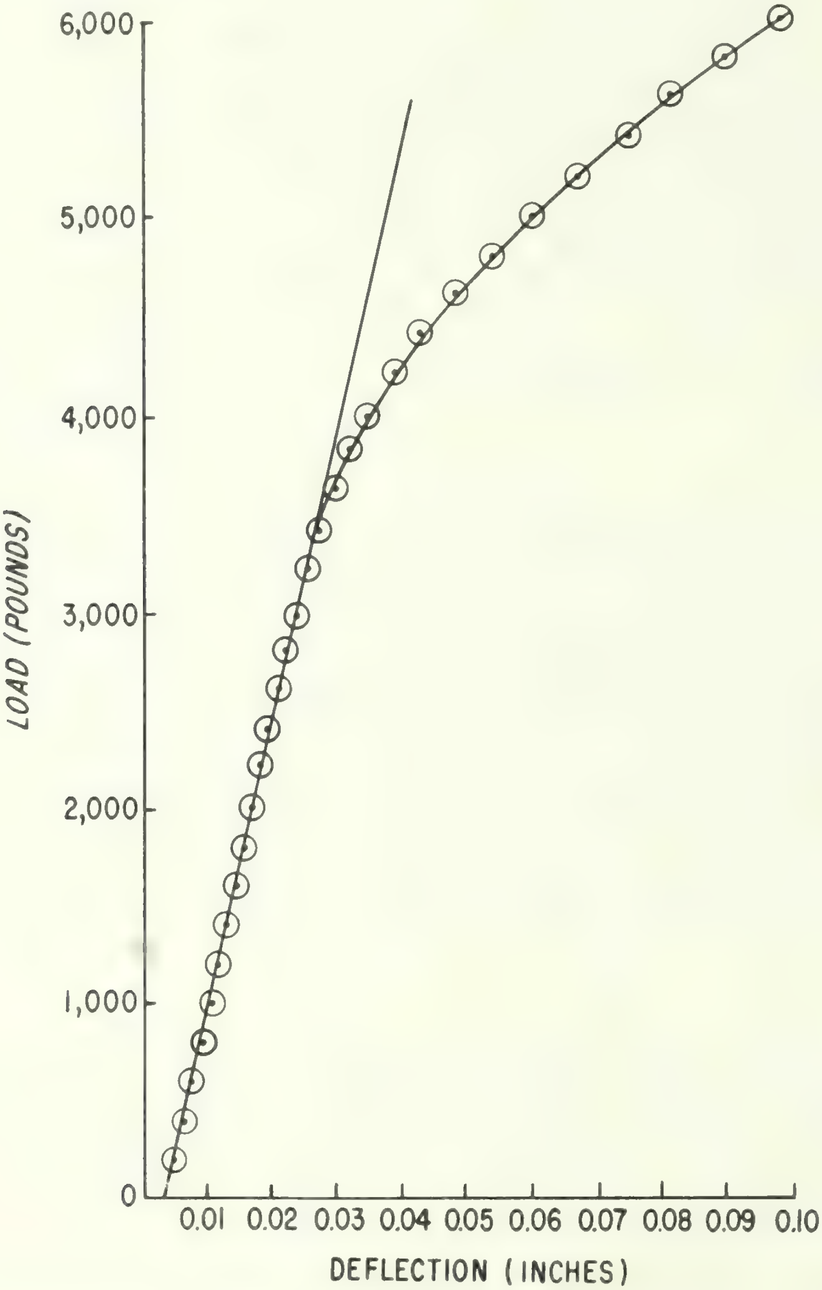

Figure 4.—Typical load/deflection curve for compression perpendicular to grain of COM-PLY studs made with hardwood veneers.

Table 5.—Values of compression perpendicular to the veneer face for COM-PLY studs made with three species of hardwood veneers

Veneer species	Stud No.	Core MOE$_b$	Average veneer MOE$_d$	Load at proportional limit	Load at 0.10-inch compression	Stress at proportional limit	Stress at maximum load
		Million lb/in^2		. . . . . . *Lb*		. . . . . *Lb/in^2*	
White oak	1	0.280	2.02	3,000	5,480	1,003	1,832
	2	.311	2.19	3,400	7,100	1,130	2,359
	5	.301	2.65	3,600	6,330	1,200	2,110
	13	.283	2.27	3,400	5,580	1,127	1,850
	15	.237	2.04	3,000	5,320	995	1,765
	Avg.	.282	2.23	3,280	5,962	1,091	1,983
	SD	.028	.255	268	745	89	248
Yellow-poplar	24	.285	2.03	2,400	5,450	805	1,829
	27	.274	1.74	2,400	5,380	797	1,786
	28	.285	2.17	2,400	4,670	803	1,563
	29	.319	2.05	3,000	6,000	1,000	2,000
	30	.276	1.83	3,000	5,640	1,000	1,880
	Avg.	.289	1.96	2,640	5,428	881	1,812
	SD	.018	.175	329	487	109	160
Sweetgum	38	.252	1.96	3,000	4,910	996	1,630
	40	.258	1.87	2,800	5,260	932	1,751
	41	.312	1.67	2,600	5,380	854	1,766
	42	.319	1.70	2,800	5,320	931	1,769
	44	.316	1.91	2,800	5,480	933	1,827
	Avg.	.291	1.82	2,800	5,270	929	1,749
	SD	.033	.129	141	217	51	72

NAILING TESTS OF COM-PLY STUDS

METHODS

Nailing tests were performed on the unbroken sections of COM-PLY studs used for performance testing. We tested lateral load on joints between plywood wall facings and the veneer faces of studs and direct nail withdrawal from the narrow faces of studs according to procedures described by Walker (1977). We did not perform tests involving the stud-to-plate joint because these values are primarily a function of the nailing characteristics of the particleboard core. The results for COM-PLY stud-to-plate joints with this core material have been published (Walker 1977).

RESULTS

The results of the lateral load tests of plywood-to-stud joints are shown in table 6. Specifications issued by the National Forest Products Association (NFPA 1977b) set the allowable lateral design load for this type of joint at 51 pounds when spruce studs are used. COM-PLY studs made with yellow-poplar, sweetgum, and white oak exceeded this minimum requirement. The same specifications give the allowable lateral design loads for Group I woods (ash, beech, maple, and oak) at 78 pounds for the kind of joints used in this test. Both sweetgum and white oak COM-PLY studs exceeded this value, and the yellow-poplar studs almost equaled it.

The results of the direct nail withdrawal tests are shown in table 7. There are no specifications for this type of test. However, the resistance to direct withdrawal of all nail types tested with COM-PLY studs made with hardwood veneers equaled or exceeded the comparable values for spruce studs in previous tests (Walker 1977).

CONCLUSIONS

COM-PLY studs made with yellow-poplar, sweetgum, and white oak veneers met the performance criteria for composite studs used in exterior walls. Thus, potential manufacturers of COM-PLY studs can use these readily available hardwood veneers to produce studs.

The engineering properties of COM-PLY studs made with yellow-poplar, sweetgum, and white oak veneers are comparable to the values for kiln-dried, stud-grade lumber of southern pine and compare favorably with COM-PLY studs made with high-quality veneer of slash pine.

COM-PLY studs made with the three tested species of veneer can be used with standard fasteners in common applications. Allowable load values per nail equal or exceed values found for spruce studs.

Table 6.—Values from lateral load test of plywood-to-stud joints for COM-PLY studs made with three species of hardwood veneers

Veneer species	Average ultimate load	Standard deviation	Adjusted load
	Lb		
Yellow-poplar	287	61	75
Sweetgum	319	45	113
White oak	269	34	101

Table 7.—Loads resulting from testing direct withdrawal of nails fastened to the narrow faces of COM-PLY studs made with three species of hardwood veneers

Veneer species	Nail type	Average ultimate load	Standard deviation	Adjusted load
			Lb	
Yellow-poplar	drywall	156	36	37
	8d common	258	42	84
	16d box	236	39	76
Sweetgum	drywall	177	11	81
	8d common	289	46	96
	16d box	291	34	112
White oak	drywall	180	25	64
	8d common	266	32	102
	16d box	214	29	77

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COM-PLY 2 × 4 studs made with veneers of yellow-poplar, sweetgum, and white oak were tested for strength and stiffness, nail-holding properties, modulus of elasticity of component parts, static bending, and compression parallel and perpendicular to the grain. All tests were conducted according to performance standards for composite studs used in exterior walls or ASTM standards. Results indicated that the tested properties of COM-PLY 2 × 4's with any of the three hardwood veneers are comparable to those of COM-PLY 2 × 4's with southern pine veneers and to 2 × 4's of solid wood.

KEYWORDS: Modulus of elasticity, strength, stiffness, bending, compression, nail-holding ability, veneer, particleboard.

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PROSPECTIVE INGROWTH OF SOUTHERN PINE BEYOND 1980

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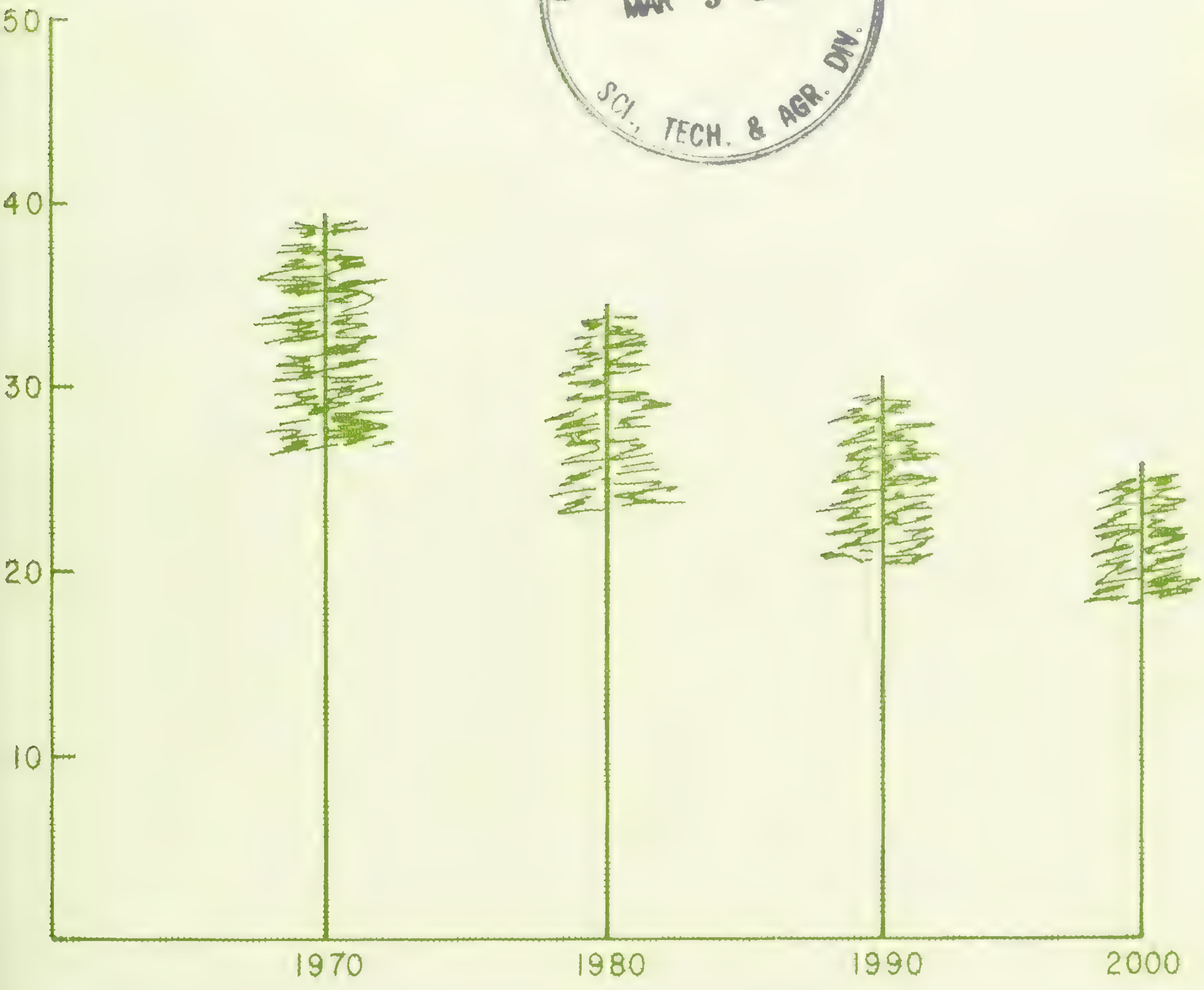

December 1979
Southeastern Forest Experiment Station
Asheville, North Carolina

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PROSPECTIVE INGROWTH OF SOUTHERN PINE BEYOND 1980

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ABSTRACT.—Between 1980 and 1990 the prospective ingrowth from 2- and 4-inch softwood trees to larger trees will be smaller than before 1974. This decline in rate of ingrowth will reduce the number of pines in the 6-inch and larger diameter classes, especially on the nonindustrial private forests. The most important action for increasing ingrowth and the future harvests of southern pines is to reestablish pines on lands when mature pines are harvested. Growing-stock volumes cannot be expected to increase until 20 to 30 years after the rate of regeneration is increased.

Keywords: Southern pine, ingrowth, pine regeneration.

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1. SUMMARY OF FINDINGS

1.1 Implications of the Findings

Ingrowth of pine saplings into the 6-inch-diameter class accounts for a large proportion of the 35 percent increase in softwood growing stock in the South between 1962 and 1977.

This relatively high rate of ingrowth resulted from high rates of pine regeneration between 1945 and 1965.

Between 1980 and 1990 the ingrowth from 2- and 4-inch softwood trees to larger diameter trees will be much smaller than prior to 1974. This reduced rate of ingrowth will reduce the number of pines in the 6-inch and larger diameter classes, and growing-stock volume in these diameter classes will decline. Prospective increases in rates of harvest, combined with reduced rates of ingrowth, can liquidate the accumulated growing-stock volume and reduce the growth/supply ratio for southern pines.

Rates of pine regeneration declined in 1965 and thereafter remained low on nonindustrial private forests (NIPF). Increased rates of regeneration on NIPF now would not make large contributions to growing-stock volumes until the year 2000, nor important contributions to roundwood supplies until the year 2010.

Current rates of pine regeneration on NIPF lands are not replacing the areas of mature pine stands that are now being harvested.

Failure to reestablish pines when most mature ones are harvested is the most important factor that transforms NIPF from pine to hardwood forest types. The stabilization of land for agricultural crops has greatly reduced rates of pine regeneration since 1965.

The most important action for increasing ingrowth and the future harvests of southern pines is to reestablish pine stands on NIPF when mature pine stands are harvested.

1.2 The Important Items of Evidence

1. Declining numbers of softwood saplings are found with each succeeding date of inventory by State after 1974 (secs. 4; 5.3; 5.5; 5.6).

2. The low rates of cropland retirement, which began about 1965, continue and, therefore, have eliminated one of the major sources of new pine stands in the South prior to 1965 (sec. 5.3).

3. Harvesting pine stands without regenerating the land to pine is the most important factor that transforms pine types to hardwood types (sec. 5.2).

4. Some kinds of partial cuttings and natural succession are also converting pine forest types to oak-pine and hardwood types (sec. 5.2).

5. The rate of conversion of pine types to

hardwood types is fastest on NIPF. Such owners hold 63 percent of the area in the important southern pine types (secs. 5.3; 5.4; 5.5).

6. Rates of planting on NIPF have remained relatively constant since 1965. Annual pine planting on NIPF is less than half the rate of natural regeneration that occurred prior to 1965 (sec. 5.4).

7. The increased rates of planting on forest industry lands will make some contribution to future timber supplies. However, forest industry lands represent only 27 percent of the commercial forest land in the important pine types (secs. 5.3; 5.4).

8. Increases in growing-stock volumes reported for 1977 resulted from rapid rates of natural regeneration prior to 1965. These growing-stock volumes can be liquidated in 10 to 20 years (secs. 3.3; 4; 5).

2. INTRODUCTION

Recent forest inventories in Southern States have revealed two apparently conflicting phenomena: (1) increases in pine growing-stock volumes, and (2) declines in the acreage in pine forest types. We have shown that the declines in acreage are associated with a sharp reduction in rates of cropland retirement; there have been no important changes in planting rates on nonindustrial private forests (Boyce 1975, 1977, 1978; Boyce and McClure 1975b; Boyce and others 1975a, 1975b; Knight 1977, 1978; U.S. Dep. Agric. For. Serv. 1978b).

We show in this Paper that ingrowth is responsible for the apparent conflict between increases in volume and declines in acreage. In forest inventories, ingrowth is the volume in trees which are above some threshold diameter now but were not during the previous inventory. Southern pines must be at least 5 inches d.b.h. before their volumes are computed and included as growing stock. It may take 15 to 30 years for a southern pine to reach this threshold. When a tree is smaller than 5 inches in diameter, its volume is considered to be 0; when it reaches 5 inches d.b.h., its volume is treated as an instantaneous accumulation.

The importance of this phenomenon to growth measurements in individual timber stands has long been recognized, but its impact on growth in entire States has not. Since ingrowth is so important in projecting southern softwood supply, we report the numbers of 2- and 4-inch softwoods estimated in recent inventories. From these data we project probable ingrowth for the future. The implications of these projections are disquieting.

3. INGROWTH AND FUTURE TIMBER SUPPLIES

3.1 Significance of the Number of 2- and 4-Inch Trees

Future supplies of softwood timber from the South are determined by the number of 2- and 4-inch pine trees that can grow through the 5-inch-diameter window and become growing stock. Numbers of 2- and 4-inch trees, of course, are determined by rates of natural and artificial regeneration. Stand density, spacing in plantations, and stagnation of young stands influence rates of mortality of 2- and 4-inch trees and affect the number of trees passing through the 5-inch window. For large areas, such as a State, rates of mortality by diameter class are relatively constant over time. The variations in natural mortality are not large enough to cause large changes in the accumulation of 2-inch trees. Although many variables are involved, the single most important indicator of future ingrowth is the number of 2- and 4-inch trees. Stand tables for successive times of inventories clearly indicate changes in rates of regeneration, ingrowth of trees that add to the growing-stock volumes, and changes in the number of trees in the large-diameter classes. These stand tables can be projected into the future if certain assumptions are made about movement of trees from smaller to larger diameter classes, about harvest of trees from the larger diameter classes, and about rates of regeneration (table 1).

In Virginia, between 1966 and 1977, the number of 2-inch softwoods declined by 10.63 trees per acre of commercial forest land (table 1), and the number of 4-inch trees declined. These declines do not influence growing-stock volumes because the trees are less than 5 inches in diameter. In fact, during this same period, the growing-stock volume in 6-inch trees increased 5.32 cubic feet per acre (table 2). This increase resulted largely from the ingrowth of trees that were previously in the 2- and 4-inch classes.

The significance of the decline in the number of 2- and 4-inch trees is that fewer trees were available for ingrowth in 1977 than were available in 1966. It is readily apparent that with current average annual rates of mortality, the number of

Table 1.–Number of softwood growing-stock trees, by diameter class, on commercial forest land in Virginia, 1966 and 1977 and projected for 1997 and 2007[1]

Diameter class (inches)	Inventory dates		Projected dates	
	1966	1977	1997	2007
	. . . . *Trees per acre*			
2	65.56	54.93	38.65	30.51
4	32.88	32.34	30.90	26.59
6	16.10	18.61	17.44	16.11
8	9.42	11.13	9.56	9.04
10	4.99	5.92	6.13	5.88
12	2.50	3.09	3.73	3.73
14	1.20	1.47	1.96	2.08
16	.54	.65	.96	1.08
18	.25	.28	.33	.38
20	.11	.11	.13	.15
22+	.07	.09	.13	.16
Total	133.62	128.62	109.95	95.73

[1] From Knight and McClure (1978).

Table 2.–Change in number and volume of softwood growing-stock trees, by diameter class, on commercial forest land in Virginia, 1966 to 1977

Diameter class (inches)	Trees per acre	Cubic feet per acre
2	-10.63	–
4	-.54	–
6	+2.51	+5.32
8	+1.71	+6.42
10	+.93	+7.55
12	+.59	+9.21
14	+.27	+6.20
16	+.11	+3.80
18	+.03	+1.50
20	–	–
Total	-5.00	+40.00

6-inch trees will decline after 1977 and the growing-stock volume in this diameter class will decline.

No action taken now can prevent a decline in the number of trees in the 6-inch-diameter class over the next 10 years. A current inventory of 2- and 4-inch trees equal to that in 1967 would be required, and we know of no method for instant creation of 2- and 4-inch trees. To maintain the number of 6-inch trees found in 1977, we would need to add immediately about 188 million 2- and 4-inch softwoods in Virginia. If efforts were begun now to bring about this increase in the number of 2- and 4-inch trees, the delay would be at least 10 years and possibly more.

Projections made by Knight and McClure (1978) illustrate how the decline in the number of 2- and 4-inch trees between 1966 and 1977 can reduce the number of 10-inch trees before 2007 (table 1). These projections are based on expected changes in the distribution of trees by diameter classes (Larson and Goforth 1970). Thus, changes in stand tables between inventories, especially changes in the numbers of 2- and 4-inch trees, are important indicators of future growing-stock volumes.

3.2 Stand Table Analysis

When the numbers of trees, by species, for a given area are plotted by diameter class (d.b.h.), the curves have a negative slope (fig. 1). The negative slope reflects the fact that relatively few small trees survive to become large ones. The slopes of the curves indicate the rates of regeneration, natural mortality as modified by harvest, and mortality from factors such as insects, diseases, and fire. Changes in rates of regeneration, indicated by an increase or decrease in the number of 2-inch trees, signal a future increase or decrease in the number of larger trees. A change in the number of trees in all diameter classes signals an increase or decrease in the rate of regeneration for a number of years. An increased steepness in the curves for the larger diameter classes indicates high rates of mortality, which may be due to increased rates of harvest. The stand curves indicate the number of 2- and 4-inch trees available as ingrowth. Thus, prospective ingrowth is indicated by the slope of the stand curves between the 2- and 4-inch-diameter classes.

It has been known for many years (Reineke 1933; Spurr 1952) that numbers of trees, by diameter classes, when plotted on log-log paper form approximately a straight line when there are equal areas of land in all age classes. Deviations from a straight line can occur whenever rates of regeneration are higher or lower than in the past. In section 4, stand table analyses are used to examine the potential for ingrowth of softwoods in 12 States.

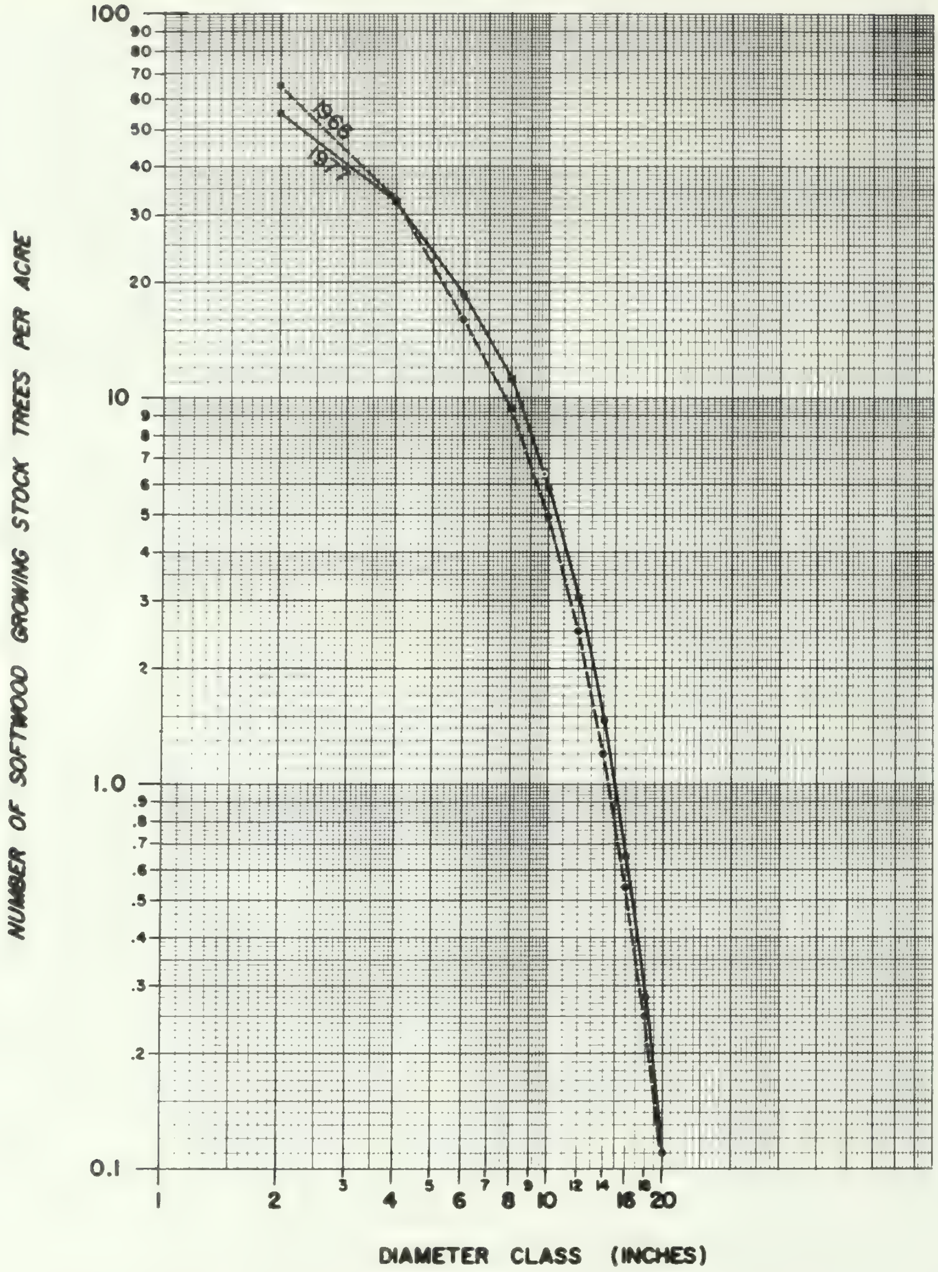

Figure 1.—Average number of growing-stock softwood trees, by diameter class, per acre, on commercial forest land in Virginia, 1966, 1977.

Figure 1 was plotted from the data in table 1. The increase in the number of trees larger than 6 inches is indicated in the chart. The increase in the number of 6-inch and larger trees indicates an increase in the amount of growing-stock volume. This amount of increase is recorded in table 2.

The chart (fig. 1) indicates the decrease in the number of 2- and 4-inch trees between 1966 and 1977. The actual decrease per average acre of commercial forest land is recorded in table 2. For Virginia, this decrease is about 188 million 2- and 4-inch softwoods.

The slope of the curves in the chart (fig. 1) for diameters below 10 inches is related primarily to the rates of natural mortality and to some harvesting. Included in the chart are data from plantations, natural stands, thinned stands, stagnated stands, and oak-pine stands. The primary reason for the decrease in 2- and 4-inch softwoods is the failure to regenerate pine after it is harvested (Boyce 1975, 1977; Boyce and McClure 1975; Knight 1978).

The increase in growing-stock volume between 1966 and 1977 can be misleading in two ways. First, the values for growing-stock volumes do not reflect the potential for ingrowth. Consequently, an increase in growing-stock volume between two inventories may be misinterpreted if potential ingrowth is ignored. Second, growing-stock volume considered as a single value for all diameter classes can be misleading. For example, in Virginia in 1977, 57 percent of the softwood growing-stock volume was in the 6- to 10-inch-diameter classes (table 3) (Knight and McClure 1978). This distribution of growing-stock volumes has several obvious implications: (1) Most of the volume of timber harvested is in trees larger than 10 inches in diameter. (2) A large increase in harvest (table 2) would likely require increased removals from the 10-inch and smaller diameter classes. (3) A primary source of volume for the 10-inch and smaller diameter classes is ingrowth. (4) The reduced numbers of 2- and 4-inch softwood trees (tables 1, 2; fig. 1) will not replace, in the next 10 years, the growing-stock volumes found in the 8- to 10-inch-diameter classes in 1977.

An increased rate of removals, especially from the 10-inch and smaller diameter classes (table 3) and a reduced rate of ingrowth (table 2; fig. 1) could rather quickly eliminate the increases reported for growing-stock volumes in 1977 (table 2). Relatively rapid reductions in growing-stock volumes in only 10 years have been reported from previous inventories.

Table 3.–Distribution of softwood growing-stock trees and associated growing-stock volumes for diameter classes 6 to 20 inches in Virginia, 1977[1]

Diameter class (inches)	Growing-stock trees	Growing-stock volume
	Percent	
6	45.1	14.7
8	27.0	21.6
10	14.3	21.0
12	7.5	17.1
14	3.6	11.9
16	1.6	7.3
18	.7	4.2
20	.2	2.2
Total	100.0	100.0

[1] Computed from tables 10 and 13 (Knight and McClure 1978). Trees larger than the 20-inch-diameter class are omitted.

3.3 An Example of Reductions in Growing-Stock Volumes

In Coastal Virginia, the volume of softwood growing stock declined between 1940 and 1956 and again between 1956 and 1966. After the 1966 inventory, the forest industries in Coastal Virginia began to procure more softwood timber from the Northern Coastal Plain of North Carolina. This action reduced the growing-stock volumes in this unit of North Carolina. In 1973 the inventory indicated the growth removal ratio in the Northern Coastal Plain of North Carolina to be 0.84. Meanwhile, the 1976 inventory found that softwood growing stock in Coastal Virginia had continued to decline, although at a slower rate than between 1956 and 1966. There are two important conclusions to be drawn from these data. First, accumulated growing stock can be liquidated in less than 10 years. Second and most important, 20 years or more are required for an increase of rate of regeneration of pines to be reflected by an increase as ingrowth to growing-stock volumes (Boyce 1977; Sheffield 1978).

In both Virginia (Boyce 1977; Sheffield 1978) and Georgia (Boyce and McClure 1975) the reduced rates of ingrowth which contributed significantly to the reduced growing-stock volumes were caused primarily by not regenerating pines after pine harvests.

3.4 Significance of Nonindustrial Private Forests

The softwood roundwood supply in the South is projected to rise from 4.2 billion cubic feet in 1976 to a much larger volume by 2030 (table 4). This increase is expected to make an important contribution to softwood supplies. The majority of the increase from the South is expected to come from NIPF. These lands include 72 percent of the commercial forest land, and they have the greatest biological potential for increasing softwood supplies (Boyce and others 1975a, 1975b). Because of this situation we give special attention to the NIPF ownerships.

4. STAND TABLE ANALYSIS FOR SOFTWOODS BY STATES

The term "softwoods" includes all softwood species found on the Forest Survey plots. Most of

Table 4.–Historic and projected softwood supplies, net annual growth, growing-stock volume, and growth/supply ratio in the South[1]

Supply	Historic values				Projected values				
	1952	1962	1970	1976	1990	2000	2010	2020	2030
	Billion cubic feet								
Softwood supply	3.0	2.7	3.5	4.2	5.1	5.9	6.7	7.2	7.50
Net annual growth	3.6	4.7	5.6	6.3	7.2	7.5	7.5	7.4	7.30
Inventory	58.2	71.5	84.9	96.8	121.1	138.1	148.6	152.9	152.10
Growth/supply	1.2	1.7	1.6	1.5	1.4	1.3	1.1	1.0	.97

[1] U.S. Dep. Agric., For. Serv. (1979).

the softwood trees are pines, and more than half of the pines are loblolly pine (*Pinus taeda* L.). Some other species, such as eastern redcedar (*Juniperus virginiana* L.), cypress (*Taxodium* spp.), hemlock (*Tsuga* spp.), and Virginia pine (*P. virginiana* Mill.) contribute to the total number of softwood trees. The plots of stand charts for the total number of softwoods for all ownerships include some trees that are not considered the most desirable for timber. The stand charts are examined in the chronological order of the inventories because the date of inventory strongly influences the results.

4.1 Stand Charts by State

In Arkansas between 1959 and 1969, there was a relatively uniform increase in the number of softwood trees in all diameter classes (fig. 2). There was no indication of a deficit in the rate of regeneration of 2- and 4-inch softwood trees. Rapid rates of cropland retirement occurred before and during this period of inventory. Most of the 2- and 4-inch trees seeded naturally onto retired cropland.

In 1970 the inventory for Florida (fig. 3) showed an increase in the number of 4-inch trees; however, the number of 2-inch trees was not much greater than in 1959. Cropland retirement in northern Florida, where most of the pines are, had continued through the early part of this inventory period.

In 1971 the data for Tennessee (fig. 4) showed a relatively constant increase in the number of softwood trees for all diameter classes. There was no indication of a deficit in the rate of regeneration of 2- and 4-inch softwood trees. Most of these pines seeded naturally onto retired cropland.

In 1972 the data for Alabama (fig. 5) showed an increase in the number of softwood trees in all diameter classes. However, the difference in the number of 2-inch trees between 1963 and 1972 was relatively small. The rate of cropland retirement declined during the inventory period.

The data for Georgia in 1972 (fig. 6) showed an increase in the number of softwood trees in all diameter classes except the 2-inch class. The 2-inch class declined almost 6 percent between 1961 and 1972. Declining rates of regeneration, associated with declining rates of cropland retirement, were described in a special study (Boyce and McClure 1975).

In 1974 the data for Louisiana (fig. 7) showed an increase in the number of softwood trees in all diameter classes. However, the increase in the number of trees in the 2-inch-diameter class since 1964 was quite small. Reduced rates of cropland retirement were beginning to become apparent in the inventory data.

In 1974 the inventory for North Carolina (fig. 8) showed a decline in the number of 2-inch trees. There was, however, an increase in the number of softwood trees in all other diameter classes.

In 1975 the inventory for Texas (fig. 9) showed a decline in the number of softwood trees in both the 2- and 4-inch-diameter classes. An increase continued to occur in the diameter classes larger than 6 inches.

In 1977 the data for Virginia (fig. 10) showed a decline in the number of softwood trees in the 2- and 4-inch-diameter classes.

In Mississippi (fig. 11) three successive in-

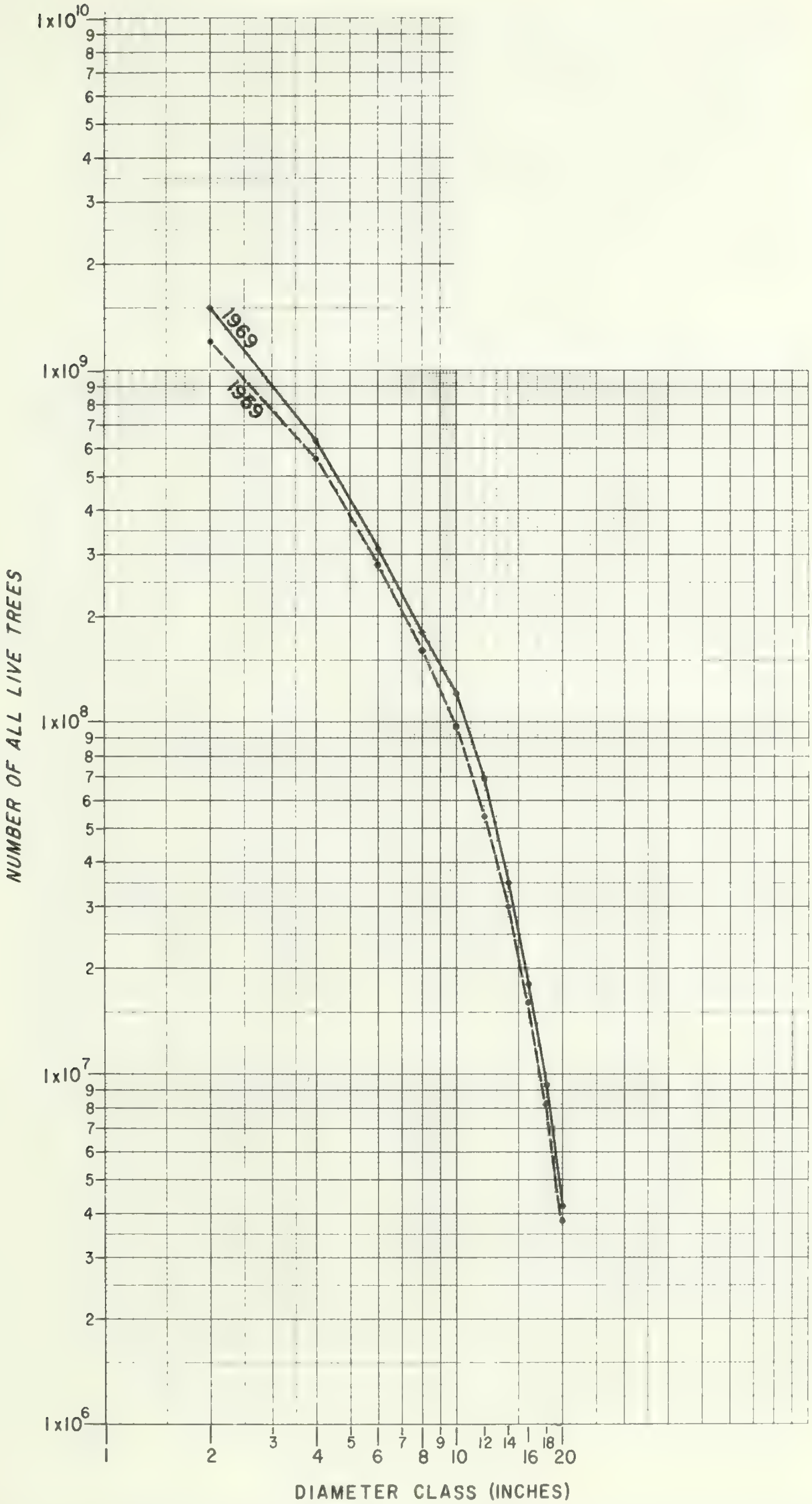

Figure 2.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Arkansas, 1959, 1969.

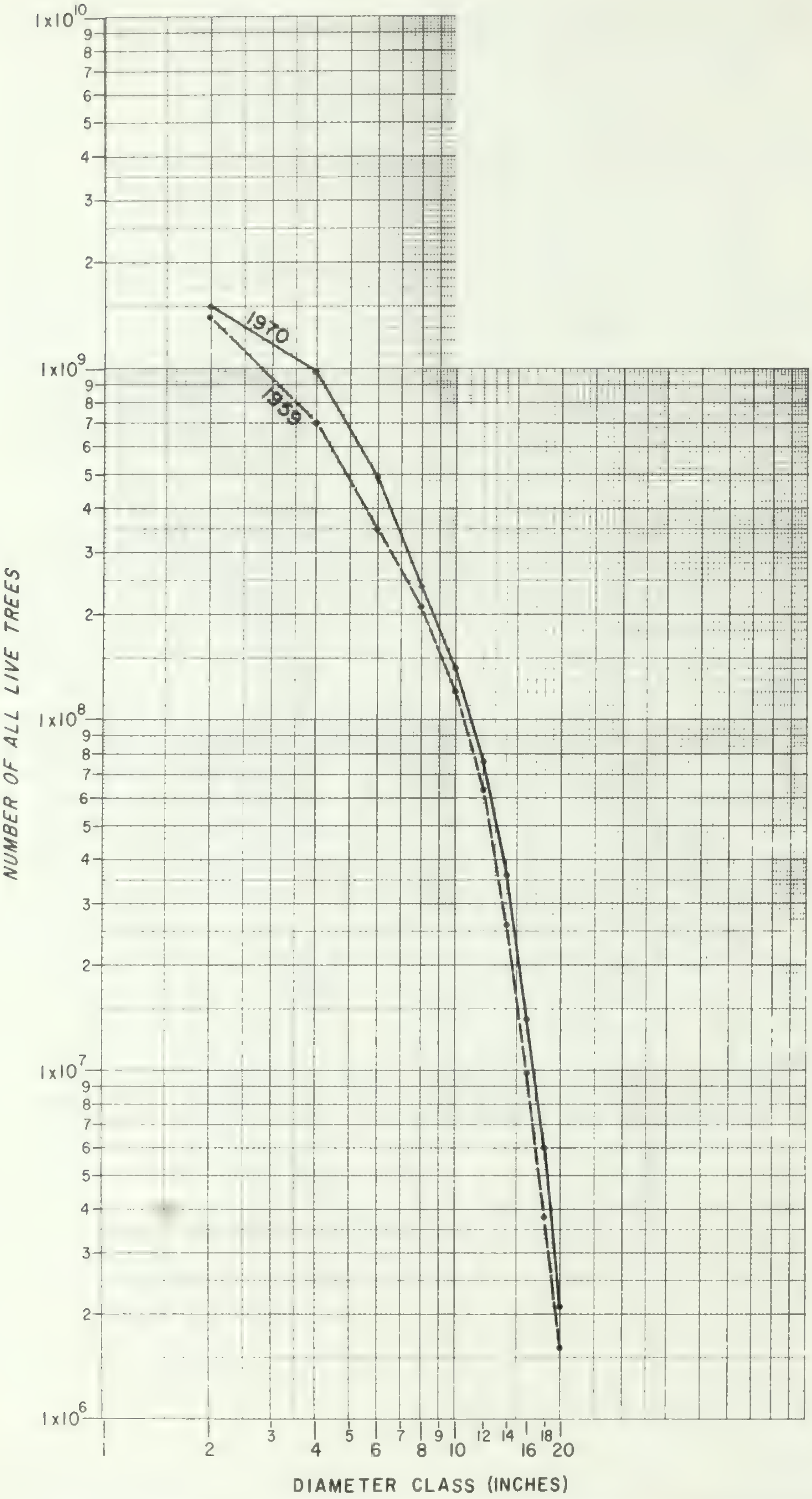

Figure 3.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Florida, 1959, 1970.

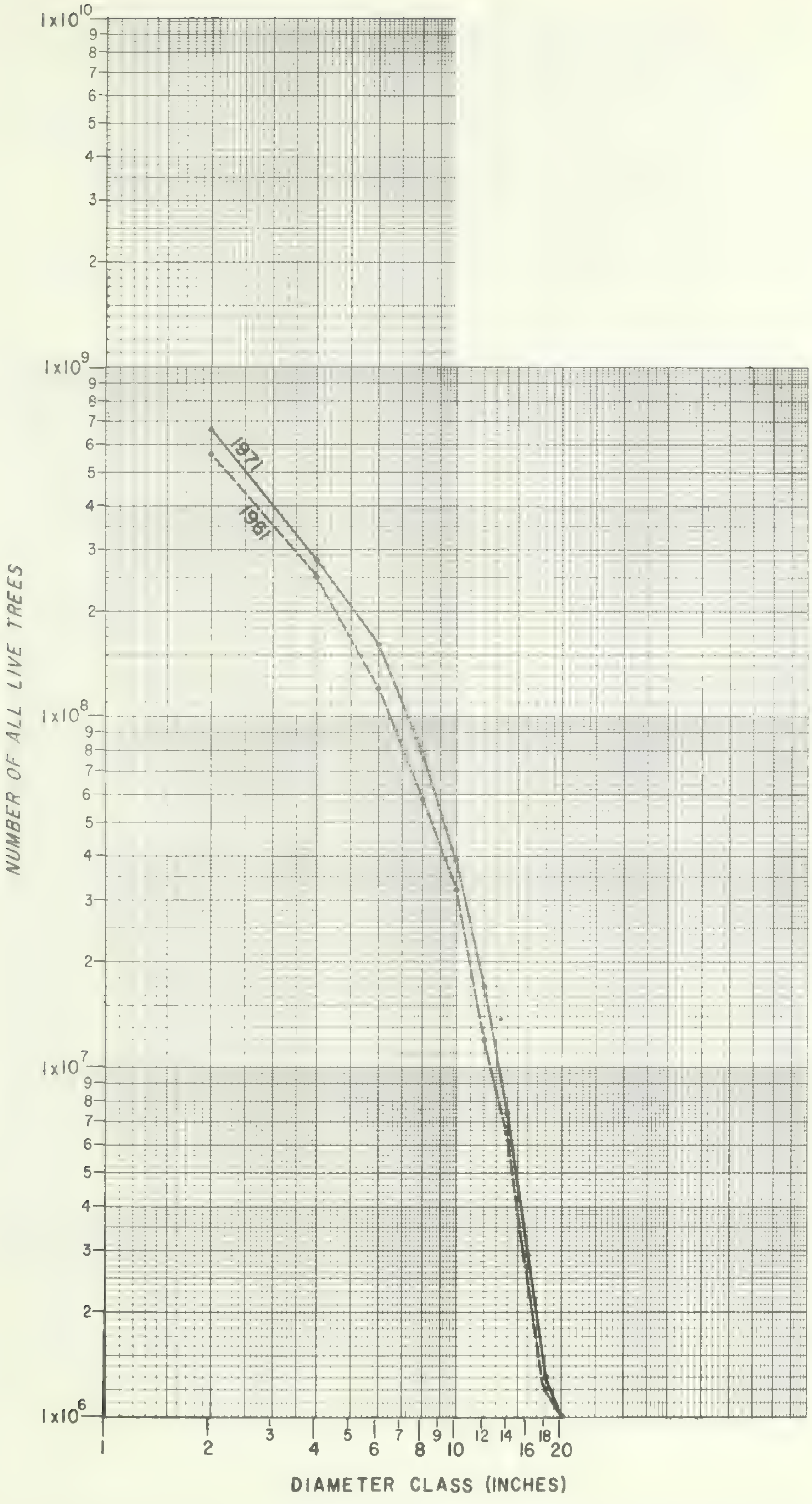

Figure 4.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Tennessee, 1961, 1971.

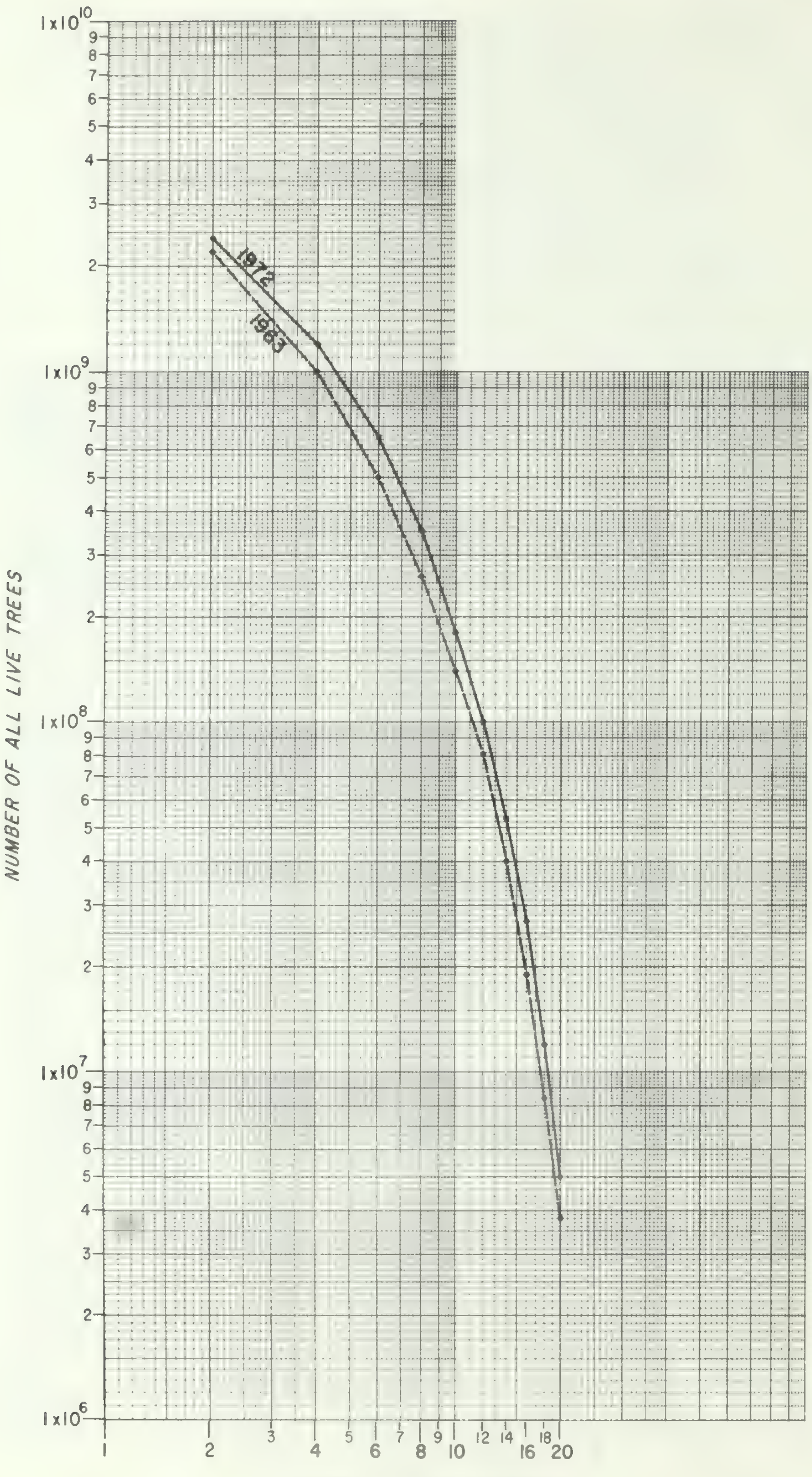

Figure 5.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Alabama, 1963, 1972.

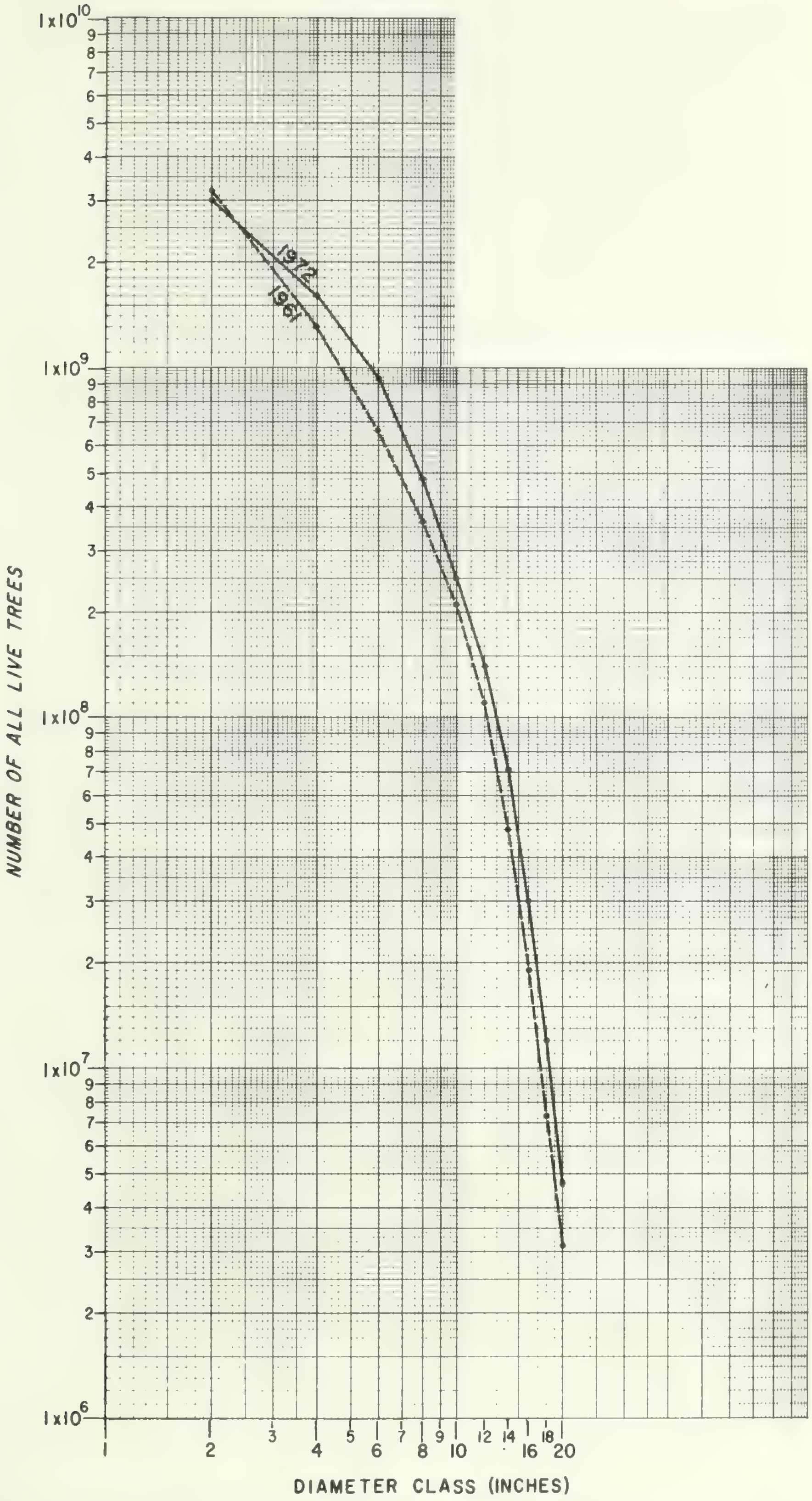

Figure 6.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Georgia, 1961, 1972.

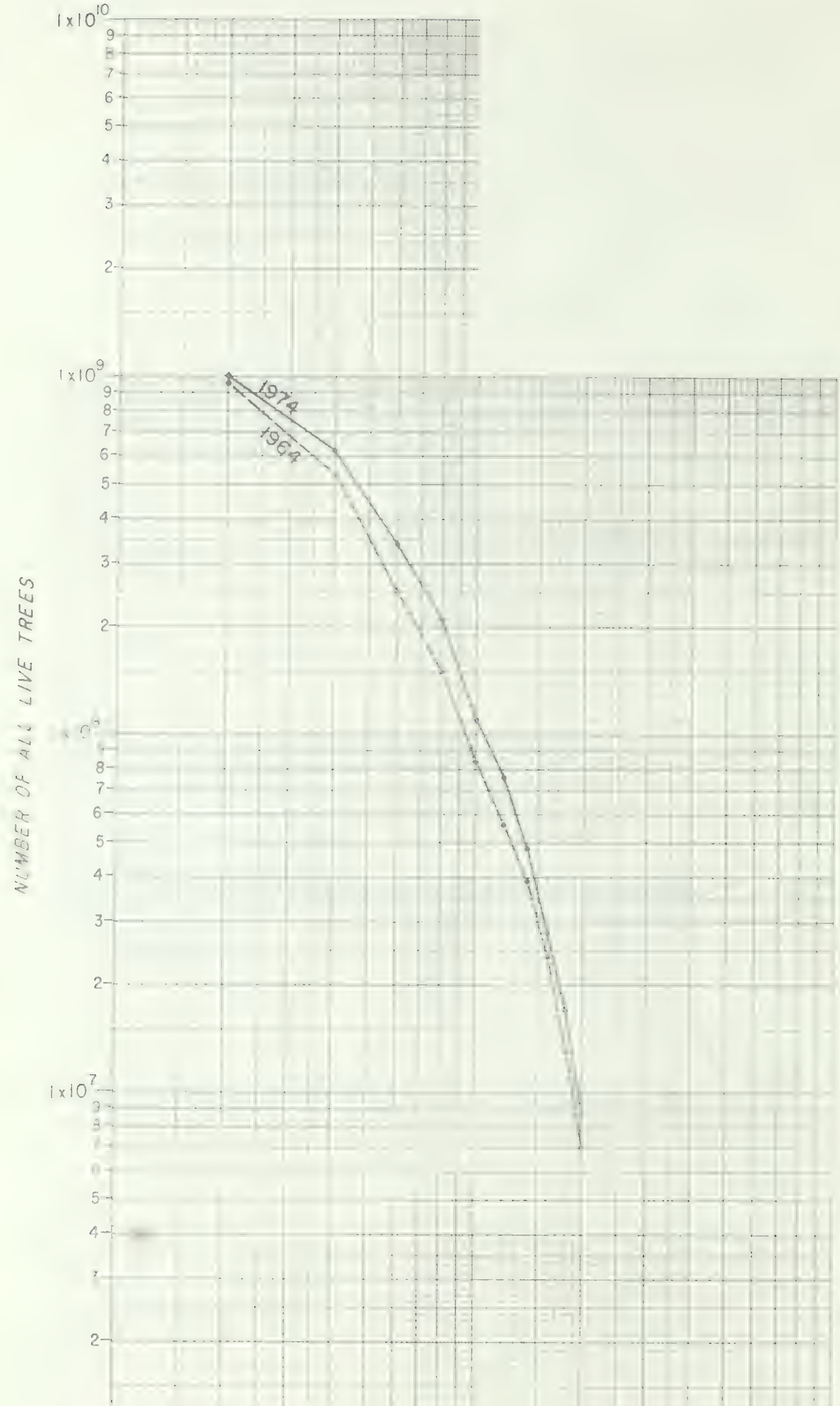

Figure 7.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Louisiana, 1964, 1974.

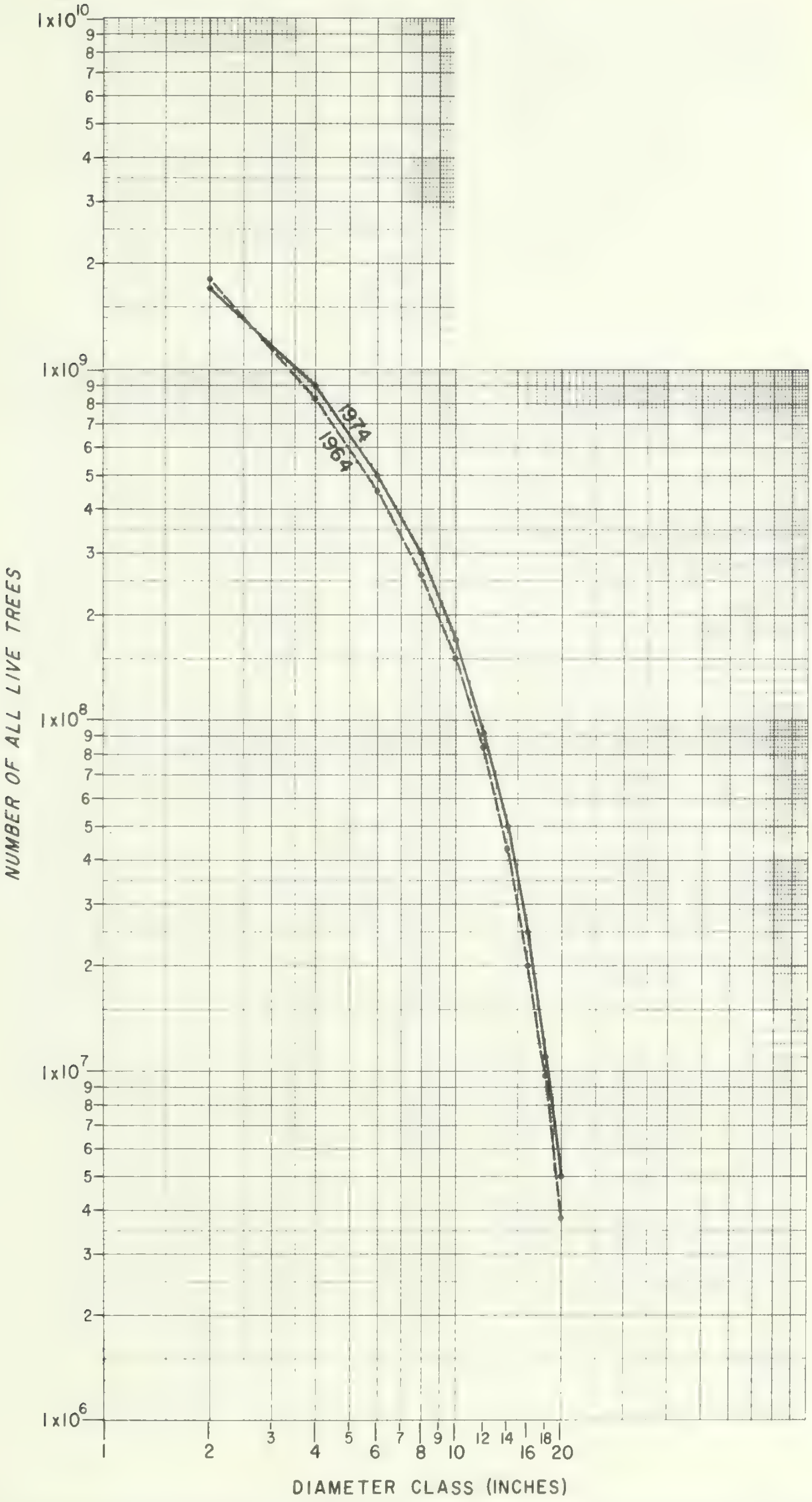

Figure 8.—Distribution of all live softwood trees, by diameter class, on commercial forest land in North Carolina, 1964, 1974.

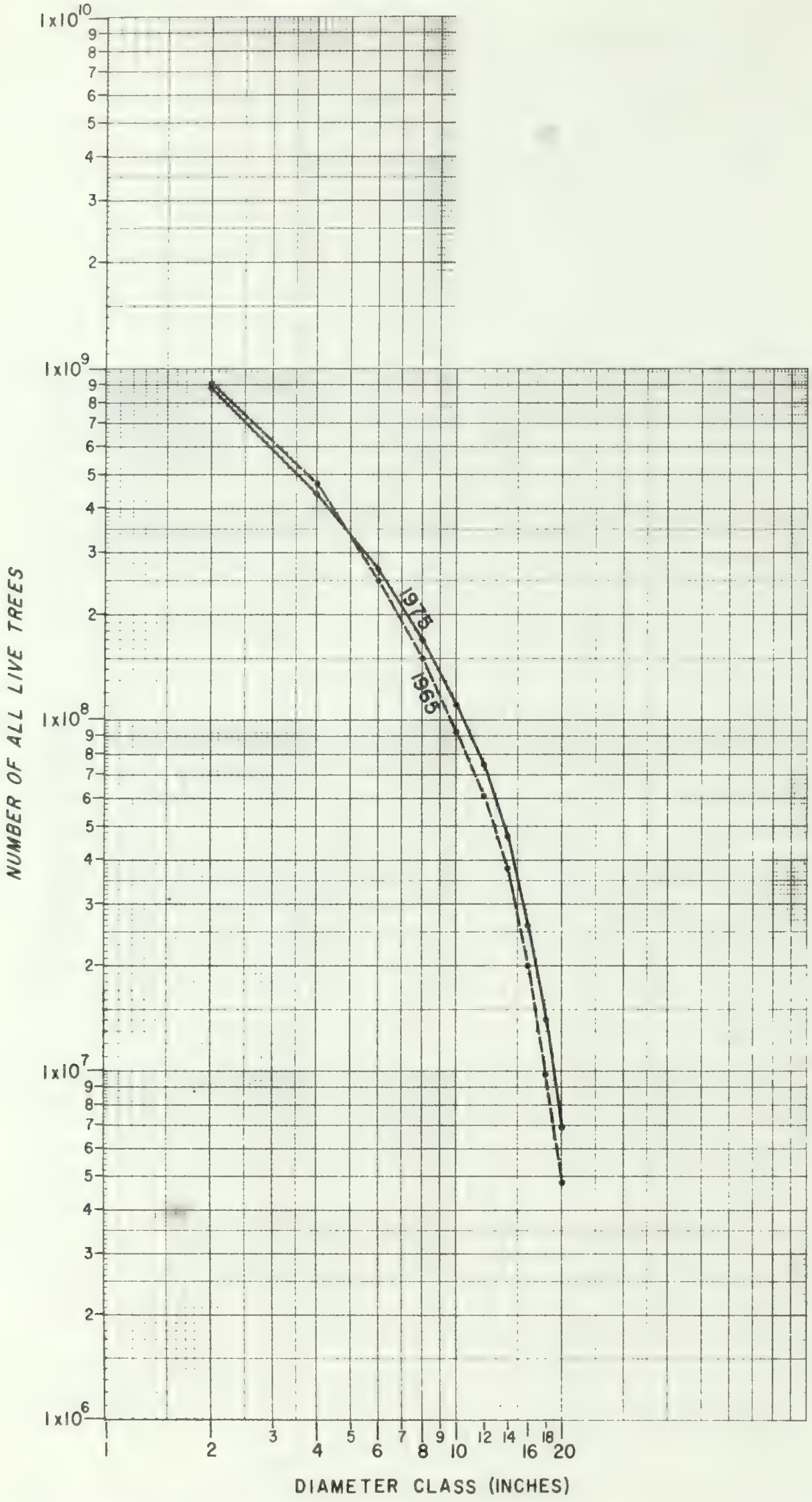

Figure 9.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Texas, 1965, 1975.

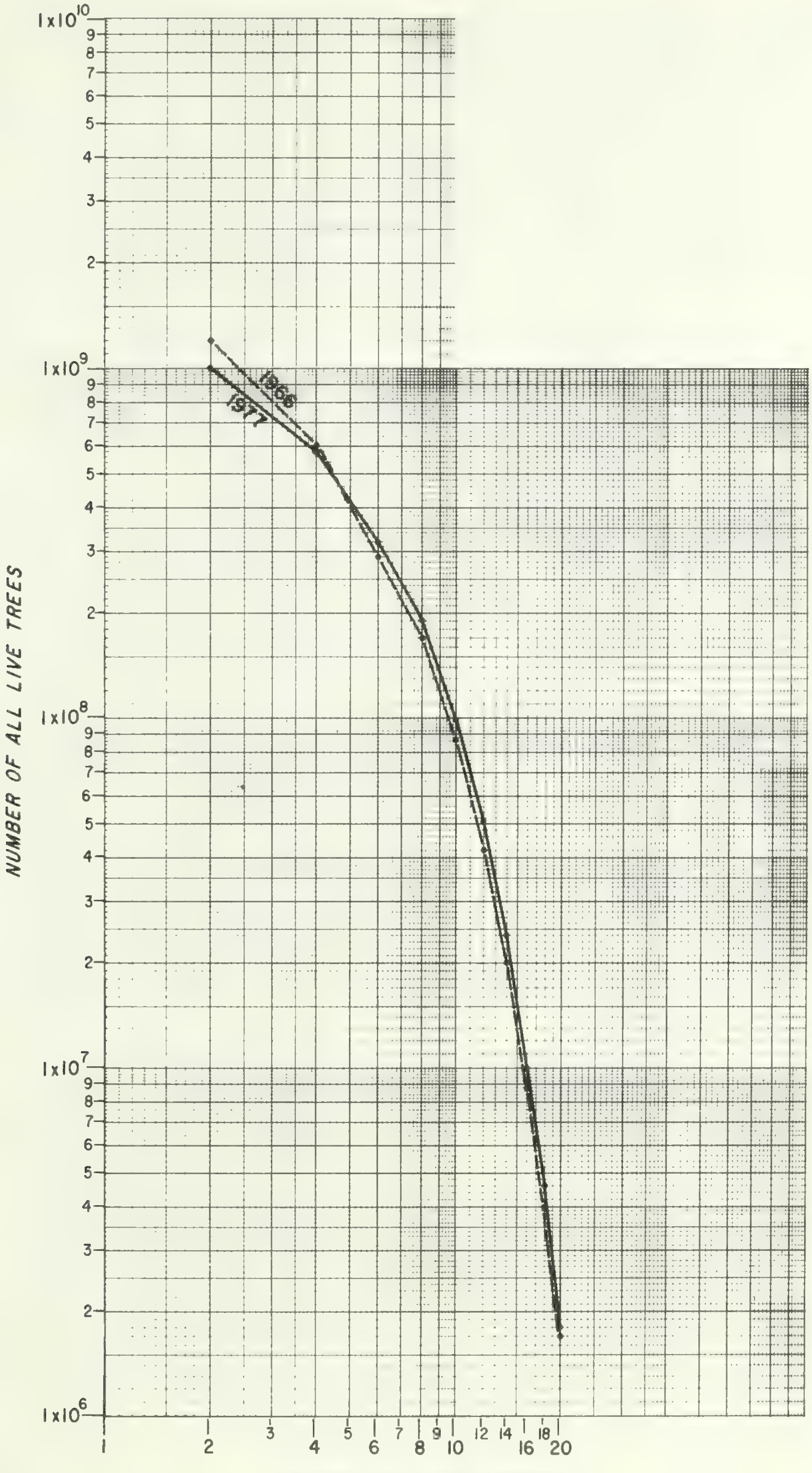

Figure 10.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Virginia, 1966, 1977.

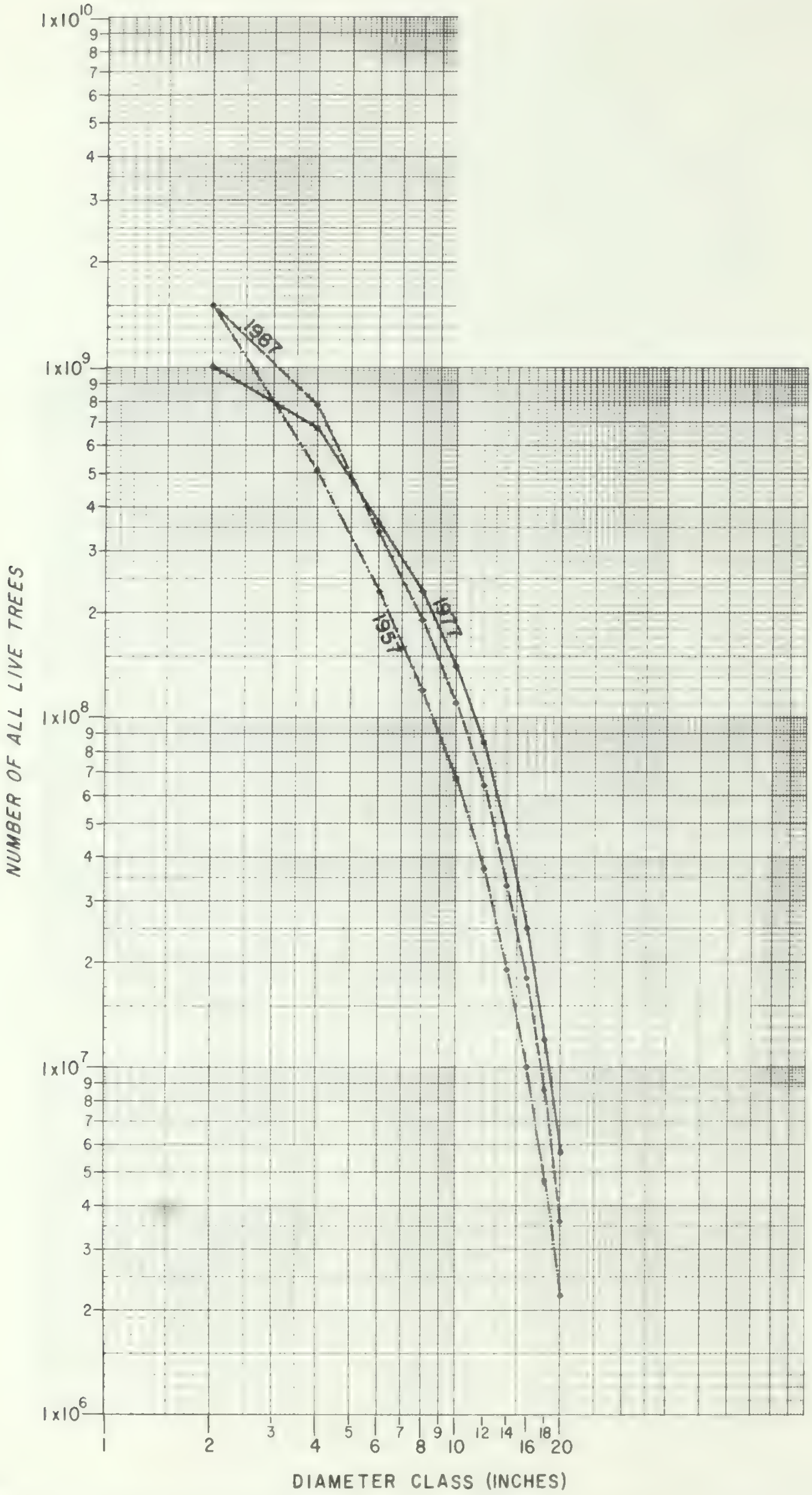

Figure 11.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Mississippi, 1957, 1967, 1977.

ventories showed a sequence of events that has been taking place in the other States. Between 1957 and 1967 a large number of 2-inch-diameter trees grew into the 4-, 6-inch, and larger trees. This change is indicated by an increase in the number of 4- and 6-inch trees in the 1967 inventory. Between 1967 and 1977 a reduction in the rate of regeneration reduced the number of softwood trees in both the 2- and 4-inch-diameter classes. Numbers of trees larger than 6 inches in diameter continued to increase through 1977 because of relatively high rates of regeneration prior to 1965. With reduced rates of regeneration since 1965 and a reduced number of 2- and 4-inch trees since 1967, we can expect lower rates of ingrowth.

In South Carolina (fig. 12), recent data agree with the trends indicated by the Mississippi charts (fig. 11). Between 1958 and 1968 a rapid rate of regeneration associated with cropland retirement (Knight 1978) increased the number of 2- and 4-inch softwoods. The 1978 inventory showed a decline in the numbers of both 2- and 4-inch softwoods. In 1978 the inventory reported 469 million fewer 2- and 4-inch softwoods than in 1968. Furthermore, the number of 6-inch softwoods increased by only 18 million trees, while the number of 8-inch softwoods increased by 66 million trees. These are in agreement with previous reports (Boyce and others 1975a, 1975b; Knight 1978) that cropland retirement between 1945 and 1965 increased the rates of regeneration of southern pines. This increased number of trees is now moving through the 6-inch and larger diameter classes and is responsible for the reported increases in growing-stock volumes (Craver 1979; Snyder 1978).

In 1965, 14 years ago, cropland retirement slowed; it has essentially stopped. And, less than half the lands from which pines are harvested are regenerated to pine (Knight 1978). This slower rate of regeneration since 1965 is now reducing the number of 2- and 4-inch softwoods. Reductions in growing-stock volumes will appear first in the 6-inch-diameter class and then move progressively through the larger diameter classes. Increased rates of removals, especially in the 10-inch and smaller diameter classes, could speed the appearance of reduced growing-stock volumes.

In eastern Oklahoma, 85 percent of the softwood growing stock is in three counties: LeFlore, McCurtain, and Pushmataha. Forest industry and public lands contain 70 percent of the softwood volume in eastern Oklahoma (Murphy 1977). Between 1966 and 1976 there was a very large increase in the number of 2-inch softwood trees in eastern Oklahoma (fig. 13). This increase occurred almost exclusively because of plantings on industrial and public lands. NIPF include relatively little pine acreage and they have a small effect on the rates of pine regeneration.

4.2 Implications of Information From the Stand Charts

Declining rates of regeneration of softwoods continue with each successive inventory. The data do not indicate when or if rates of regeneration will stabilize. Planting and natural rates of regeneration should maintain some minimum number of softwood trees for many decades. This minimum number of trees is not indicated by data now available. A continuing decline from the present number of pines can be expected.

Growing-stock volumes continued to increase through 1978, but the number of 6- and 8-inch trees will decline by 1990 because of a reduced rate of ingrowth.

The number of 10-inch and larger trees will decline between 1990 and 2000 because of the smaller number of 6- and 8-inch trees that will be available for growing into the larger diameters. Increased harvest of softwoods from the South could speed the appearance of decreased growing-stock volumes.

5. FACTORS ASSOCIATED WITH THE REGENERATION OF SOUTHERN PINES

5.1 The Softwood Timber Species

The loblolly (*P. taeda* L.) and shortleaf (*P. echinata* Mill.) pine types represent the most important sources of softwood timber from the South. These types occupy about 49 percent of the area in softwood types in the South (table 5). They contain 67 percent of the net growing-stock volume. Loblolly is the most common pine and is the one that must make the greatest contribution to future supplies of softwood timber from the South.

The longleaf (*P. palustris* Mill.) and slash (*P. elliottii* Engelm.) pine types represent about 18 percent of the total area in softwoods and about 17 percent of the net growing-stock volume. Slash pine and longleaf pine will continue to be impor-

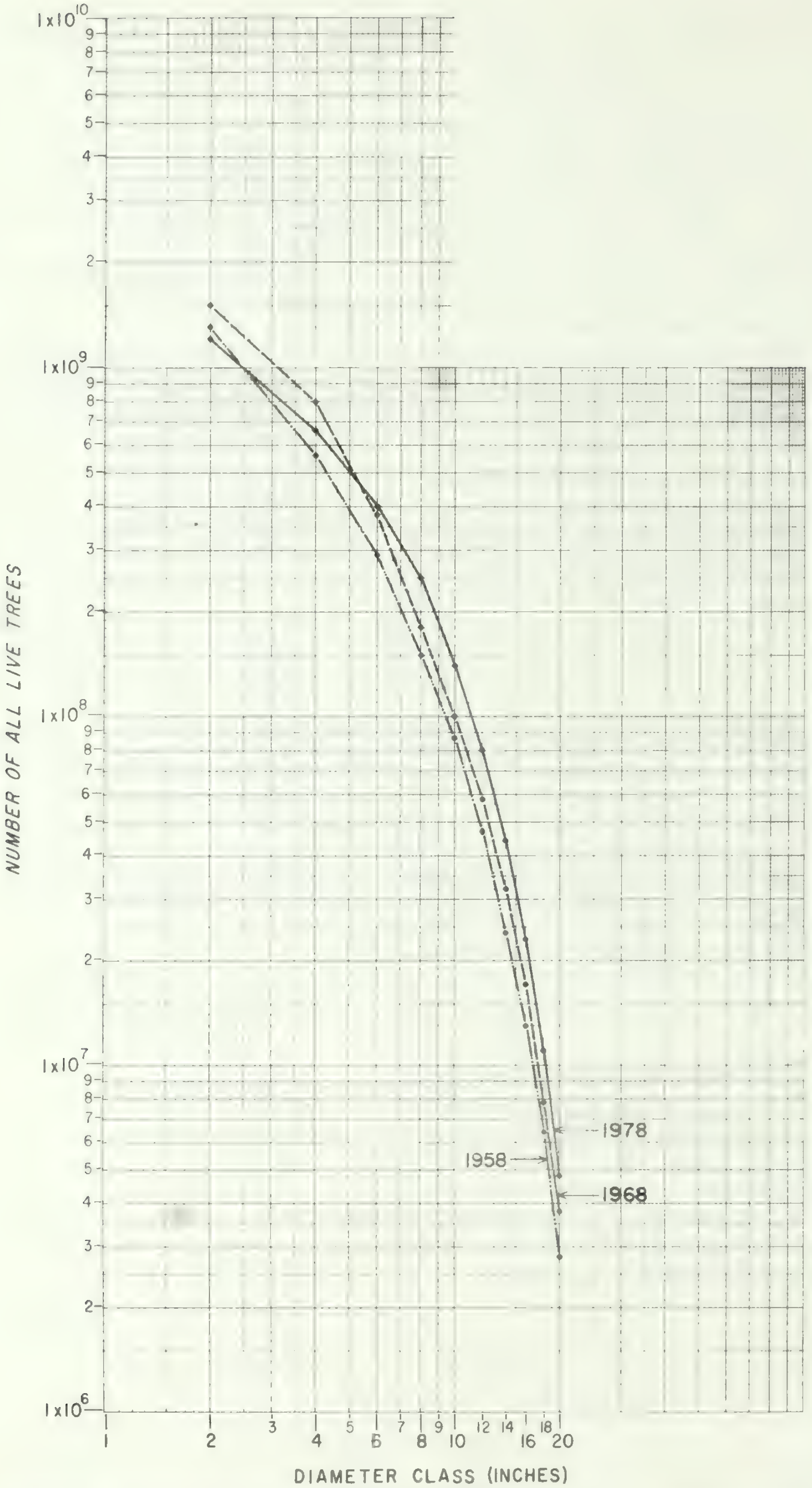

Figure 12.—Distribution of all live softwood trees, by diameter class, on commercial forest land in South Carolina, 1958, 1968.

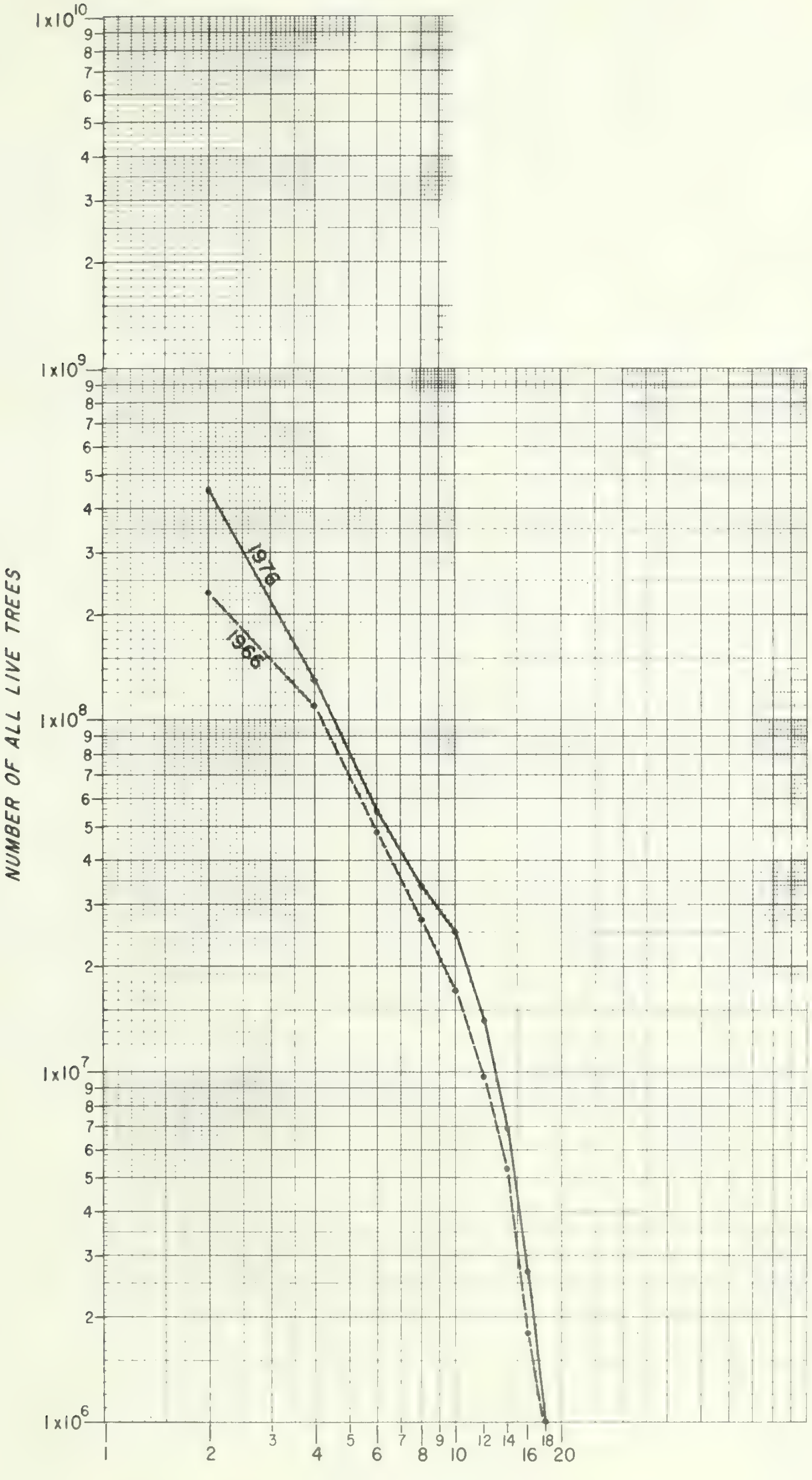

Figure 13.—Distribution of all live softwood trees, by diameter class, on commercial forest land in Oklahoma, 1966, 1976.

Table 5.—Distribution of softwood area growing-stock volume, by softwood forest type, in the South, 1977[1]

Forest types	Area		Growing stock	
	Million acres	*Percent*	*Billion cubic feet*	*Percent*
Loblolly-shortleaf	46.5	49	64.1	67
Longleaf-slash	17.0	18	16.8	17
Other softwoods	[2] 30.8	33	15.9	16
All softwoods	94.3	100	96.8	100

[1] U.S. Dep. Agric., For. Serv. (1978a).
[2] Mostly the oak-pine type, which has 51 to 74 percent of the stocking in hardwoods.

tant timber species, but the primary species for softwood timber is loblolly pine.

We are particularly interested in changes in rates of regeneration for loblolly pine and slash pine, because these two species are the ones usually considered for intensive forest management. Changes in the rates of both natural and artificial regeneration of these two species provide important information about future supplies of softwood timber from the South (Boyce and others 1975a, 1975b).

5.2 The Land Base for Pines

Since 1965, when cropland retirement essentially stopped in the South, the acreage of commercial forest land there has been declining (table 6). Since 1962 the decline has been about 11.5 million acres for all forest types. However, for the pine forest types, which represent only about one-third of the commercial forest land, the decline is 16.6 million acres (table 7). The primary cause of this decline was the failure to regenerate pine after pine stands were harvested (Boyce 1975; Boyce and McClure 1975; Knight 1978).

In Georgia between 1961 and 1972, harvesting, partial cuttings, and natural succession accounted for 70 to 79 percent of the conversion of slash pine and loblolly pine types to other types of land uses (tables 8, 9). Most of these conversions were to oak-pine, oak-hickory, and bottomland hardwood types (Boyce and McClure 1975). Similar trends were found in North Carolina and Virginia (Boyce and McClure 1976), and in the Piedmont of South Carolina (table 10). Harvesting without regenerating the land back to pine types is the most important cause for a reduction in the land base for pine in the South.

A reduction in the land base for pine, caused by forestry activities that convert pine types to hardwood types, can result in a rapid reduction in

Table 6.—Trends in area of commercial forest land in the South, by region and year

Region	Year			
	1952	1962	1970	1977
	Thousand acres			
South Atlantic	46,963	47,912	48,463	47,677
East Gulf	42,104	43,128	41,334	40,142
Central Gulf	49,497	53,361	51,454	51,045
West Gulf	53,519	55,505	51,291	49,569
Total	192,083	199,906	192,542	188,433

Table 7.—Area of commercial forest land in major pine types in the South, 1963 and 1977

Region and type	1963[1]	1977[2]	Change
	. . . . *Thousand acres*		
South Atlantic:			
Longleaf-slash	3,597	1,578	-2,019
Loblolly-shortleaf	14,924	13,630	-1,294
East Gulf:			
Longleaf-slash	15,814	11,407	-4,407
Loblolly-shortleaf	7,641	7,983	+342
Central Gulf:			
Longleaf-slash	4,162	2,790	-1,372
Loblolly-shortleaf	13,998	11,876	-2,122
West Gulf:			
Longleaf-slash	2,404	1,241	-1,163
Loblolly-shortleaf	17,614	13,051	-4,563
South:			
Longleaf-slash	25,977	17,016	-8,961
Loblolly-shortleaf	54,177	46,540	-7,637
Total	80,154	63,556	-16,598

[1] U.S. Dep. Agric., For. Serv. (1965).
[2] U.S. Dep. Agric., For. Serv. (1978a).

Table 8.—Rotation of land from loblolly pine in Georgia, by type of action, 1961 to 1972[1]

Type of action	Area affected	Area rotated to another use	
	. . . . . *Thousand acres*		*Percent*
Harvest	947.8	513.0	33
Partial cuttings	1,395.6	356.5	23
Natural succession	2,008.6	352.2	23
Urbanization	138.6	138.6	9
Agriculture	126.3	126.3	8
Disturbance	460.9	69.5	4
Total	5,077.8	1,556.1	100

[1] From Boyce and McClure (1975).

Table 9.–Rotation of land from slash pine in Georgia, by type of action, 1961 to 1972[1]

Type of action	Area affected	Area rotated to another use	
	..... *Thousand acres*		*Percent*
Harvest	943.6	372.7	34
Natural succession	1,157.7	253.8	23
Partial cuttings	995.1	146.6	13
Urbanization	123.9	123.9	11
Agriculture	112.9	112.9	10
Disturbance	769.2	91.2	9
Total	4,102.4	1,101.1	100

[1] From Boyce and McClure (1975).

Table 10.--Rotation of commercial forest land from pine type in the South Carolina Piedmont, by type of action, 1967 to 1977[1]

Type of action	Area affected	Area rotated to another use	
	.... *Thousand acres*		*Percent*
Harvest	412.4	192.3	42
Natural succession	989.8	88.2	20
Partial cuttings	583.0	86.0	19
Disturbance	364.5	55.3	12
Agriculture	18.5	18.5	4
Urbanization	14.3	14.3	3
Total	2,382.5	454.6	100

[1] From Knight (1978).

the number of 2- and 4-inch trees. Eventually, growing-stock volume and the supply of southern pine timber also decline. About 1965 the rate of pine regeneration in the South rapidly declined, and the rate of conversion of pine forest types to hardwood types rapidly increased. Thus, 1965 marks an important change in the rate of regeneration of southern pines. This change is important in the development of assumptions for projecting net growth, inventory, and growth supply ratios.

The area of commercial timberland with yellow pine and oak-pine forest types in the 2- and 4-inch-diameter classes declined 19 percent between 1970 and 1977 (table 11). Almost all of this decline, 7.7 million acres, occurred on NIPF, which include 63 percent of the commercial forest land in pine types (table 12).

5.3 Change in Rates of Regeneration of Southern Pines After 1965

About 1965 the land base for agriculture in the South became relatively stable (table 13) (Boyce and others 1975a, 1975b). Shifting agriculture no longer assured natural regeneration of pines on millions of acres of retired cropland (table 14). Also, in the absence of shifting agriculture, hardwood forests were no longer cleared, Table 11.–Trends in area of commercial timberland in yellow pine and oak-pine forest types in the South, by ownership class and stand size, 1970 and 1977[1]

Ownership class and stand size	Year		Change	
	1970	1977	Area	Percent
	Thousand acres			
Public:				
Sapling and seedling	2,171	2,144	-27	-1.2
Poletimber	2,140	2,434	+294	+13.7
Sawtimber	4,884	4,667	-217	-4.4
All sizes	9,195	9,245	+50	+0.5
Forest industry:				
Sapling and seedling	8,991	9,293	+302	+3.4
Poletimber	4,543	5,864	+1,321	+29.1
Sawtimber	10,217	8,255	-1,962	-19.2
All sizes	23,751	23,412	-339	-1.4
NIPF:				
Sapling and seedling	28,277	20,528	-7,749	-27.4
Poletimber	14,928	19,972	+5,044	+33.8
Sawtimber	22,501	20,786	-1,715	-7.6
All sizes	65,706	61,286	-4,420	-6.7
All ownerships:				
Sapling and seedling	39,439	31,965	-7,474	-19.0
Poletimber	21,611	28,270	+6,659	+30.8
Sawtimber	37,602	33,708	-3,894	-10.4
All sizes	98,652	93,943	-4,709	-4.8

[1] U.S. Dep. Agric., For. Serv. (1978a).

Table 12.–Distribution of all commercial forest land in the South and of major pine types, by ownership class, 1977[1]

Ownership class	Total	Pine types
	. . . *Percent*	
Public	9.4	10.1
Forest industry	19.0	26.7
NIPF	71.6	63.2
All owners	100.0	100.0

[1] U.S. Dep. Agric., For. Serv. (1978a).

Table 13.–Area of cropland harvested in the South, by State and year[1]

States	1976	1977	1978
	. . . . *Thousand acres*		
Va., N.C., S.C., Ga., Ala., Tenn.	23,254	22,616	24,182
Tex., Okla.	31,244	33,178	29,584
Ark., La., Miss.	18,180	18,923	18,908
Fla.	1,436	1,358	1,471
Total	74,114	76,075	74,145

[1] From Crop Production, 1978 Annual Summary, Economics, Statistics, and Cooperative Service, U.S. Dept. Agric. (1979).

Table 14.–Reported reductions in cropland harvested and age distribution of pine stands in the South Carolina Piedmont, 1977[1]

Period (years)	Reduction[2]	Age[3]	Area
	Thousand acres	*Years*	*Thousand acres*
1944-49	260.6	26-30	242.2
1949-54	343.5	21-25	264.5
1954-59	325.0	16-20	225.1
1959-64	210.5	11-15	166.0
1964-69	150.1	6-10	189.9
1969-74	[4](-48.3)	0-5	126.2
1944-74	1,241.4	0-30	1,213.9

[1] From Knight (1978).

[2] Summarized from Census of Agriculture statistics.

[3] Stand-age classifications made between April–September 1977.

[4] Area of cropland harvested increased.

farmed, retired, and naturally regenerated to pine. Between 1945 and 1965, about 1.5 million acres of cropland were retired annually. After 1965 the rate of cropland retirement dropped to 0.2 million acres per year and now is essentially 0. Plantations that could once be established on retired cropland must now be established after some kind of site preparation.

Not only is the establishment of pine plantations more costly because of the requirement for site preparation, but the need for plantations is greater because fewer areas are naturally seeding to pine. If we examine changes in the numbers of 2- and 4-inch softwood trees by States and years of inventory (sec. 4.1), we find declining rates of softwood regeneration with successive inventories. This relationship is consistent for all States except Oklahoma (fig. 14).

Although the period of rapid cropland retirement ended about 1965, inventories for States were still showing an increase in the number of 2- and 4-inch softwoods for 9 years, until 1974. After 1974, inventories consistently show declines in the number of 2- and 4-inch softwood trees (fig.

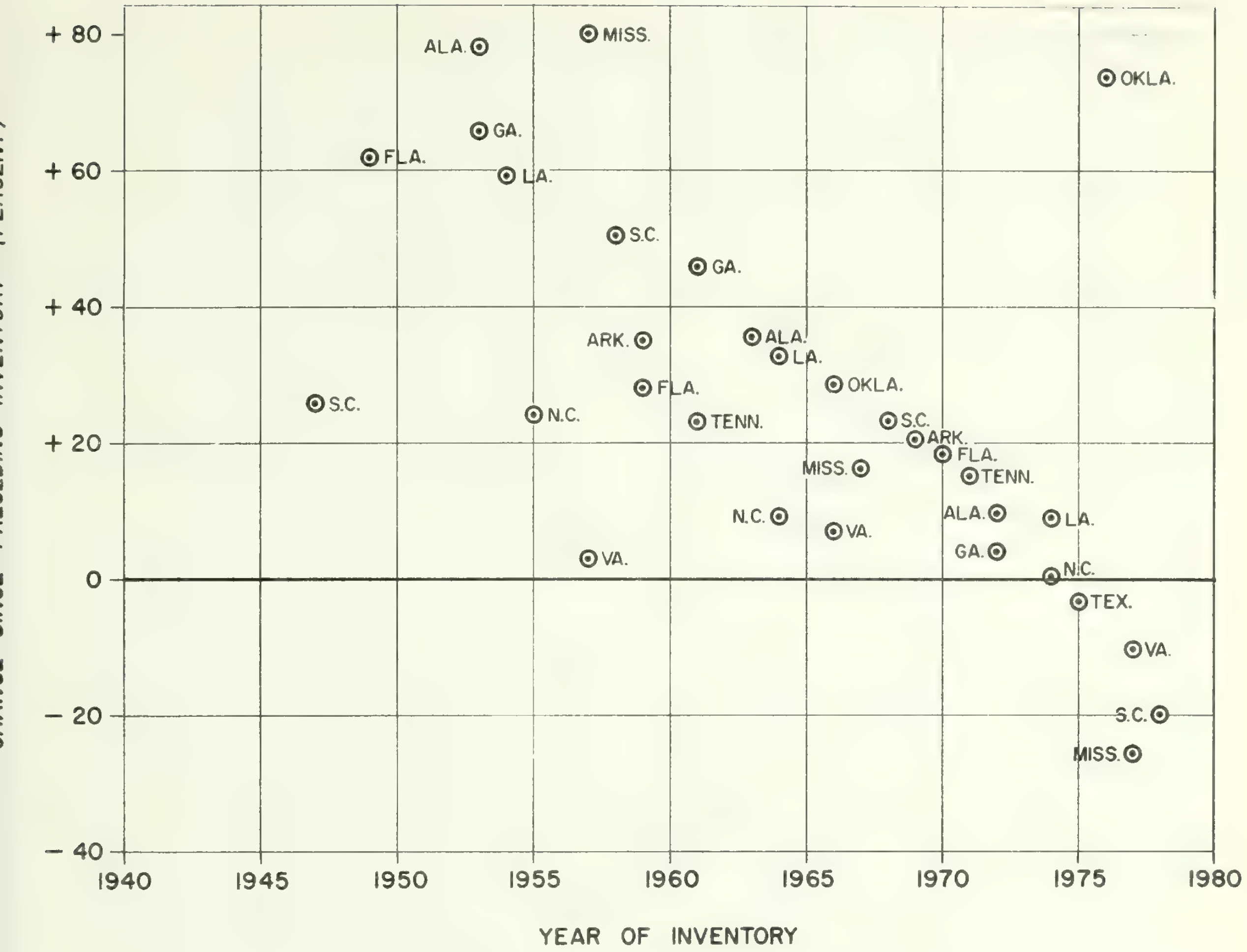

Figure 14.—Percent change in the number of softwood trees in the 2- and 4-inch-diameter classes, by State and year of inventory.

14). Shortfalls in natural regeneration will begin to appear in inventories in 10 to 15 years. Thus, declines in numbers of 6-inch and larger softwood trees can be expected after 1980. And, by about 1985 inventories should begin to indicate a decline in softwood growing-stock volumes in the 6- and 8-inch-diameter classes. By 1995 significant declines in growing-stock volumes can be expected, because this will be 30 years after the beginning of lower rates of regeneration.

Declines in rates of softwood regeneration are indicated also by examining changes in the number of 2-inch trees for four to five inventories (figs. 15, 16). Virginia, North Carolina, South Carolina, and Georgia show a decline in the number of 2-inch softwoods proportional to the time between 1965 and the date of the last inventory. Again, the data indicate the significance of a reduced rate of regeneration after 1965.

The last Florida inventory was 1970 and more than half of the inventory period was prior to 1965. The increase in the number of 2-inch softwoods for this period was relatively small. The next inventory for Florida should indicate whether rates of softwood regeneration in this State also declined after 1965.

5.4 Regeneration of Pines by Classes of Landowners

Are current rates of pine regeneration fast enough to replace pine stands that are expected to be harvested in coming years? Since cropland retirement has practically stopped, the regeneration of pines must be primarily by site preparation and planting after harvest of pine stands and by the conversion of oak-pine and hardwood types to pine. The decline in natural regeneration of pine and the increase in the rate of planting are indi-

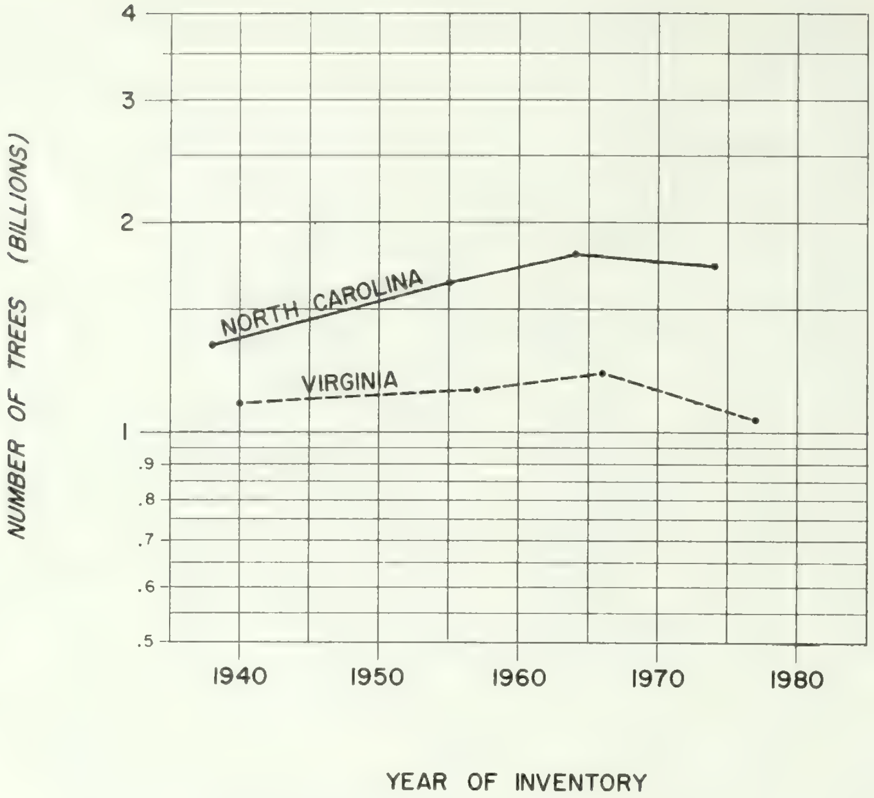

Figure 15.—The number of softwood trees in the 2-inch-diameter class, by year of inventory, for North Carolina and Virginia.

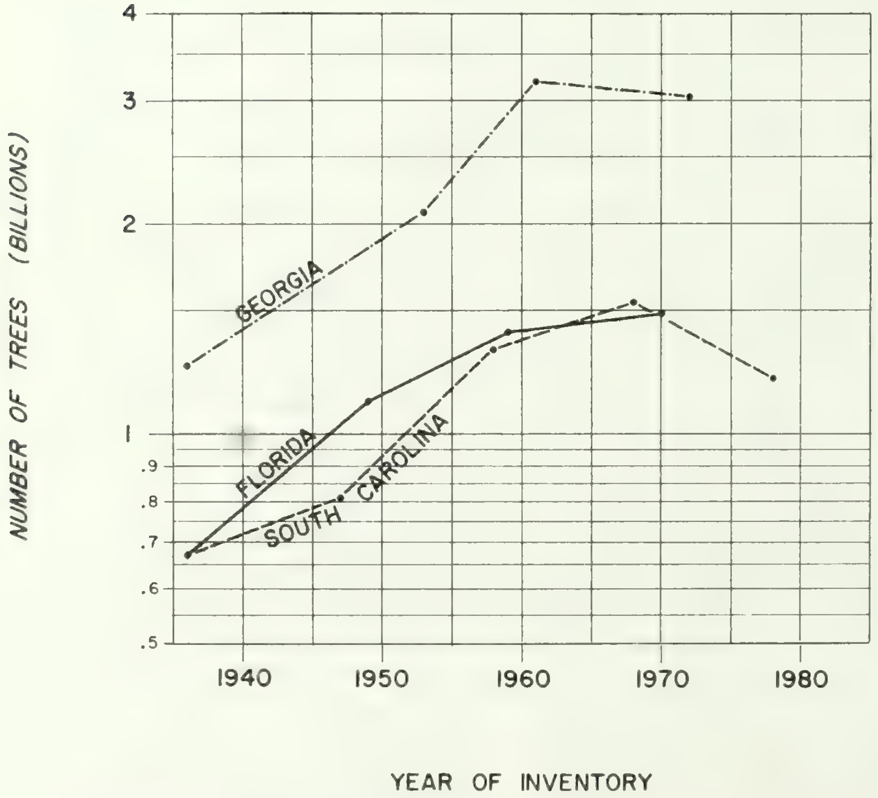

Figure 16.—The number of softwood trees in the 2-inch-diameter class, by year of inventory, for Georgia, Florida, and South Carolina.

cated by recent data from North Carolina, Virginia, and South Carolina (table 15). During the past 20 years, the rate of natural regeneration in pine in these States has been declining quite rapidly. During the same period, the rate of planting of pine has been increasing.

A number of planted areas have poor stocking and are classified as nonmanageable stands (table 15). The number of acres reported to have been planted does not, therefore, represent the number of planted acres considered to have a manageable stand of trees.

Since 1965, about 12.5 million acres of land in the 12 Southern States were reported to be planted (table 16). We can assume that practically all of these acres were planted to pine—mostly loblolly. More than half of these planted acres are owned by forest industry. About one-fourth of the plantings are on NIPF.

Only the forest-industry class of ownership shows a dramatic increase in rate of planting since 1965 (table 16; fig. 17). The public class of ownership shows some increase after 1970. However, acres of NIPF planted fluctuate considerably between 1965 and 1977 and no definite trends are apparent.

Between 1965 and 1973 the planting of trees on NIPF was encouraged through Federal cooperative programs with the States and under the agricultural conservation programs. In 1973 the Agriculture and Consumer Protection Act included a Forestry Incentives Program. However, after 1974 the data show no important increase in the rates of forest planting on NIPF (fig. 17).

Some holdings of corporations, which do not participate in the forestry incentives programs, are included in the NIPF class of ownership. If we remove the corporate holdings, it should be possible to more accurately identify changes due to forestry incentives programs. Table 17 includes trees planted only by persons and nonprofit clubs. A number of States show relatively small increases in numbers of acres planted between 1975 and 1978, compared with 1965 to 1968. States that showed definite increases in acres planted from 1975 to 1978, compared with 1965 to 1968, are Virginia, Texas, and Oklahoma. For the other States, differences between these two periods of time are relatively small. Only in Virginia have numbers of acres planted increased consistently since 1971. This increase is likely related to the enactment of the Reforestation of Timberlands Act in 1970 (Sheffield 1978). Most of the increase in total acres planted between 1975 and 1978 can be related to increases in Virginia and Texas.

Table 15.–Area of land in pine plantations and in natural pine stands, by stand age, State, and year

Stand-age class (years)	North Carolina, 1974		Virginia, 1977		South Carolina, 1978	
	Planted	Natural	Planted	Natural	Planted	Natural
	Acres					
No manageable stand	27,241	634,586	11,791	122,222	61,299	390,235
Less than 10	633,036	518,055	419,793	288,533	409,633	267,497
10–19	319,979	729,687	209,807	351,261	428,375	389,812
20–29	28,539	815,059	33,940	483,724	377,830	806,679
30-39	5,028	1,062,732	4,381	518,943	70,952	1,003,218
40–49	–	956,890	–	426,448	13,063	766,588
50-59	–	580,160	–	275,550	1	317,702
60–69	–	299,264	–	187,455	3,229	154,020
70-79	–	154,368	–	62,847	–	62,462
80-89	–	96,806	–	33,609	–	31,437
90+	–	43,158	–	7,184	–	16,888
All classes	1,013,823	5,890,765	679,712	2,757,776	1,364,382	4,206,538

Table 16.–Acres of trees planted in the South, by ownership class, 1965-77[1]

Year	Public	Forest industry	NIPF	Total
	Thousand acres			
1965	89	360	258	707
1966	89	358	250	697
1967	84	390	296	770
1968	88	459	249	796
1969	91	519	197	807
1970	91	572	262	925
1971	113	704	184	1,001
1972	114	618	258	990
1973	112	664	247	1,023
1974	111	693	216	1,020
1975	112	867	272	1,251
1976	104	816	252	1,172
1977	97	908	296	1,301
Total	1,295	7,928	3,237	12,460

[1] From Reports of Forest Planting, Seeding, and Silvical Treatments in the U.S., U.S. Dep. Agric., For. Serv. 1965 to 1978.

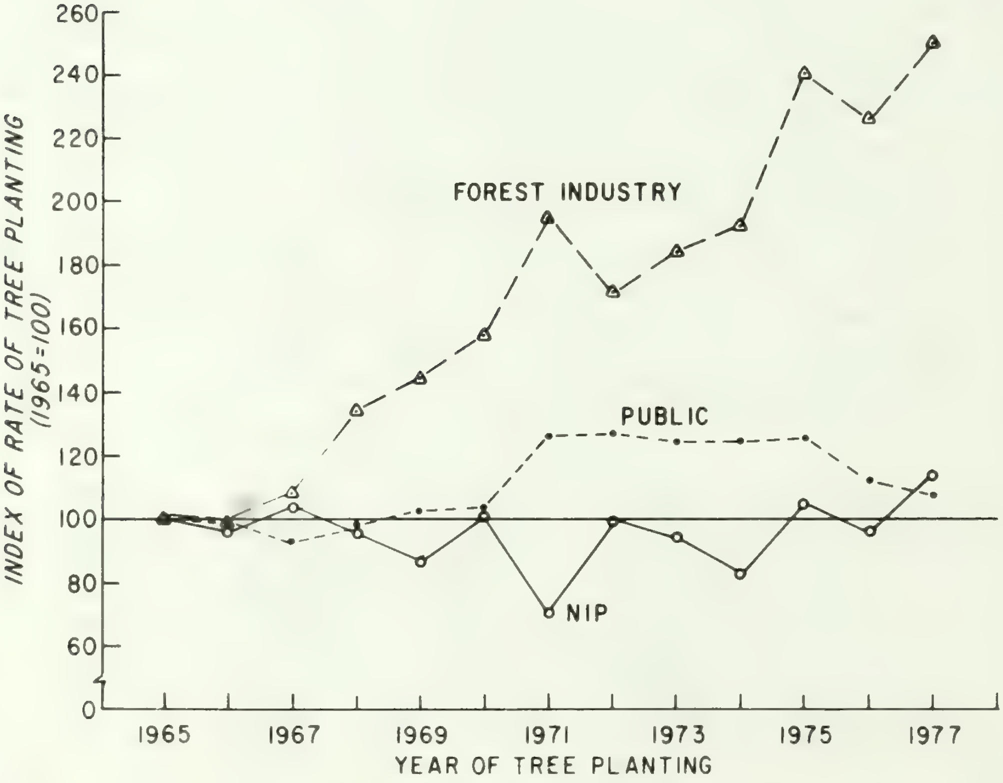

Figure 17.—Change in the rates of tree planting, by three classes of ownership, in 12 Southern States since 1965. The base values for 1965 are: Forest industry = 360,291 acres; Public = 89,366 acres; NIPF = 258,594 acres.

Table 17.–Acres of trees planted on lands owned by persons and nonprofit clubs since 1964, by State and year

State	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
							Thousand acres							
Alabama	18.8	25.9	38.1	37.2	23.0	23.8	22.6	29.4	29.9	19.2	25.2	22.2	28.6	28.3
Arkansas	7.6	9.6	4.6	6.4	.3	7.1	3.7	3.9	5.9	5.1	7.3	9.2	13.3	9.0
Florida	23.6	24.3	39.6	32.7	22.2	24.7	13.7	26.3	25.4	50.4	34.6	29.4	22.9	17.4
Georgia	29.1	26.5	42.6	29.5	24.3	13.8	18.4	18.3	20.1	13.6	29.4	22.3	23.0	26.2
Louisiana	7.0	5.8	5.9	7.1	8.6	5.1	10.9	9.8	10.8	5.1	6.6	5.2	12.0	8.2
Mississippi	38.0	41.2	39.7	34.0	20.3	37.3	29.5	30.0	29.6	22.8	26.5	32.2	41.8	45.4
North Carolina	18.5	18.3	24.8	14.6	34.7	17.7	15.8	20.1	15.8	12.8	28.9	32.3	32.1	26.5
Oklahoma	.9	.7	.3	.4	.6	1.0	1.0	1.6	1.1	.6	.6	1.5	1.3	2.9
South Carolina	26.4	20.8	29.6	16.7	9.5	9.5	8.2	7.9	9.4	6.3	13.9	10.0	16.4	23.6
Tennessee	14.6	14.1	12.8	10.4	6.4	6.7	6.6	7.1	8.8	8.8	5.2	6.0	6.6	6.2
Texas	5.4	1.2	1.9	2.2	5.4	3.5	3.3	5.3	4.9	3.5	9.7	9.6	16.2	14.7
Virginia	28.4	25.2	26.3	23.9	24.8	27.5	32.5	53.1	43.7	47.0	52.4	48.3	53.3	54.4
Total[1]	218.3	213.6	266.2	215.1	180.1	177.7	166.2	212.8	205.4	195.2	240.3	228.2	267.5	262.8

[1] The difference between these values and those for the NIPF–ownership class in table 18 is the lands owned by nonforest industries and corporations.

These data provide evidence that the rates of forest planting on NIPF for most of the 12 Southern States are about the same as they were 10 years ago. Planting is not compensating for the loss of natural regeneration that was brought about by reduced rates of cropland retirement.

The relatively low rates of planting pines on NIPF can be illustrated in another way. For each ownership class we estimate the average number of acres planted per year for the last 5 years, 1973 to 1977, and divide this average into the acres in important forest types owned. The result is the number of years required to plant an area equal to the important pine types (table 18). The current rate of planting on forest-industry lands can replace the important pine types in only 21 years. On public lands the replacement time is 60 years. However, on NIPF lands 156 years are required to replace the important forest types at current rates of planting.

Table 18.–Relative rates of forest planting in the South, by ownership class

Ownership class	Acres of important pine forest types owned[1]	Average number of acres planted per year, 1973-1977[2]	Years to plant in important pine types
Public	6,445	107	60
Forest industry	16,961	790	21
NIPF	40,149	257	156

[1] U.S. Dep. Agric., For. Serv. (1978a). Includes only loblolly-shortleaf and longleaf-slash pine types.
[2] From table 16, this Paper.

5.5 The Regeneration of Pines in Mississippi

The latest survey for Mississippi was completed in 1977. The data for 1967 and 1977 provide an opportunity to examine recent trends in rates of pine regeneration by classes of ownership.

5.5.1 Loblolly Pine

Loblolly pine is the most important softwood species in Mississippi. Between 1966 and 1977 the number of loblolly pine trees declined about 8 percent (table 19). Most of this decline occurred on the farm woodlots. Although there was a small increase in the number of trees larger than 8 inches in diameter, there was a large decline in the number of 2-, 4-, and 6-inch trees (fig. 18). The outlook is for a smaller number of trees larger than 6 inches in diameter on Mississippi farms, a reduced rate of ingrowth to growing-stock trees, and a reduction in growing-stock volumes.

This miscellaneous-private class of ownership, consisting primarily of people who are not dependent on the land for a living, had about the same number of loblolly pine trees in 1977 as in 1967 (table 19). However, the distribution of trees by diameter classes changed (fig. 19). The number of trees larger than 6 inches in diameter increased, while the number of 2- and 4-inch trees decreased. The large increase in the number of trees larger than 10 inches in diameter suggests that this class of landowners is not marketing pine timber as rapidly as farmers in Mississippi. However, miscellaneous-private owners appear to be regenerating loblolly pine at a higher rate than farmers.

There was a small net increase in the number of loblolly pine trees on the forest industry lands between 1967 and 1977 (table 19). The increase was in trees between 4 and 12 inches in diameter, yet there was a 22 percent decrease in the number of 2-inch-diameter trees (fig. 20). Much of the decline in 2-inch trees on forest-industry lands may be attributable to the heavy reliance on planting by forest industry. Plantations typically contain far fewer trees per acre when they are young than do natural stands. Relatively high rates of mortality, delays between harvest and regeneration, and fusiform-rust infections may also contribute to reduced numbers of 2-inch trees per unit area.

There is an increase in the number of loblolly pine trees on National Forest lands (table 19). This increase is primarily in the 2-inch-diameter class (fig. 21). At the same time, there is no important decrease in the number of larger diameter

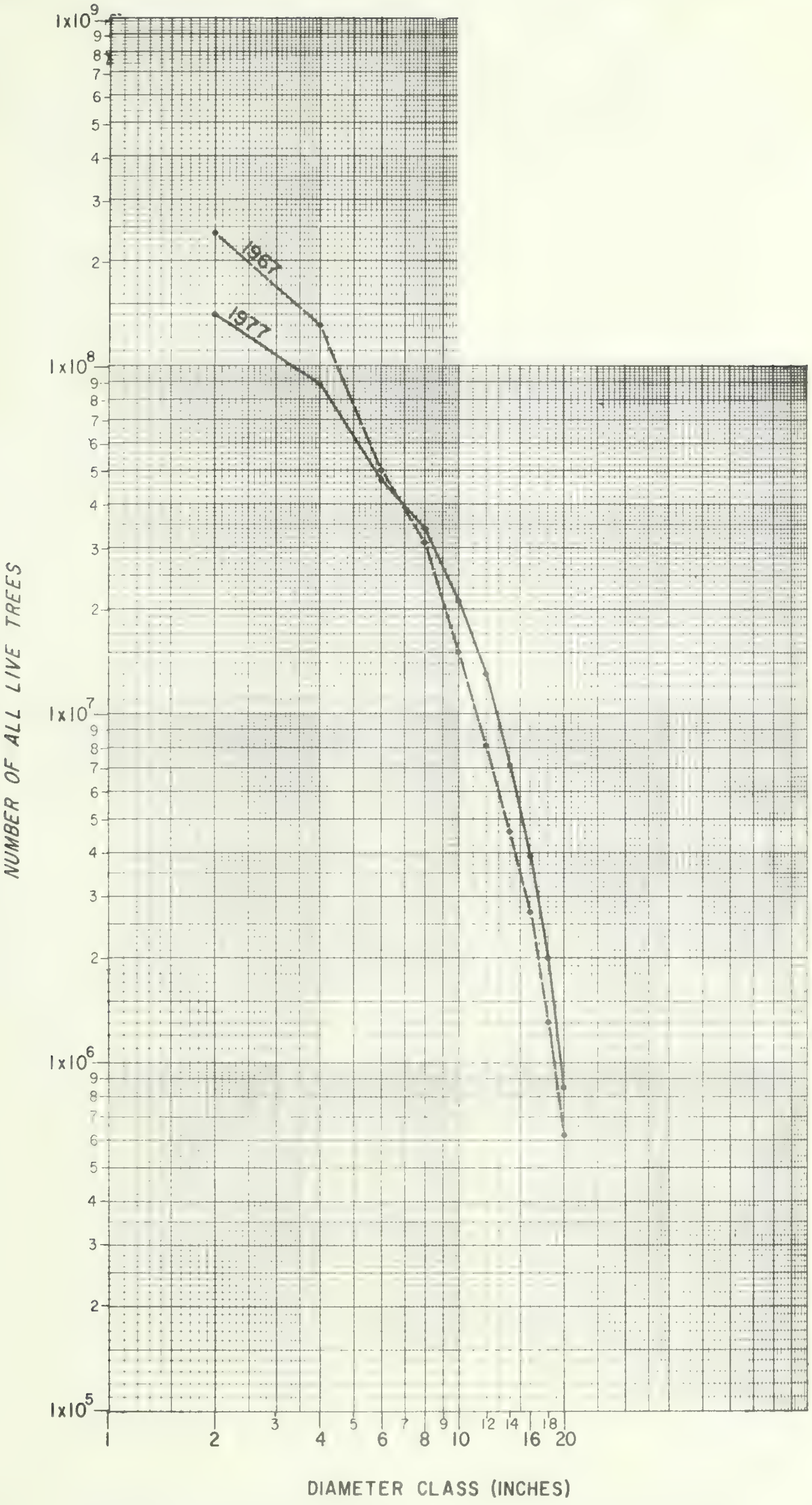

Figure 18.—Distribution of all live loblolly pine trees, by diameter class, on farmer ownerships in Mississippi, 1967, 1977.

Table 19.–Number of all live loblolly, shortleaf, slash, and longleaf pines in Mississippi, by ownership class, 1967 and 1977

Ownership class	Loblolly		Shortleaf		Slash		Longleaf	
	1967	1977	1967	1977	1967	1977	1967	1977
	Millions							
Farmer	489.6	358.0	401.3	207.8	37.8	16.6	27.1	14.3
Miscellaneous private	602.6	606.6	445.5	343.6	73.0	72.6	49.0	37.0
Forest industry	275.0	285.0	129.4	118.5	108.9	93.2	29.1	24.4
National Forest	91.3	100.3	59.0	61.0	26.2	30.6	27.4	38.3
Other public	33.1	23.7	11.6	4.5	4.4	9.0	3.6	1.8
Total	1,491.6	1,373.6	1,046.8	735.4	250.3	222.0	136.2	115.8

trees. We can expect only a small increase in future growing-stock volumes on these lands because of the relatively small land area in public ownership in Mississippi.

5.5.2 Shortleaf Pine

Between 1967 and 1977, the number of shortleaf pine trees declined 30 percent (table 19). Declines occurred in all ownership classes except National Forests, where they remained about the same throughout the period. During the period, little effort was made to encourage the planting and the natural regeneration of this species. On farm woodlots, numbers of trees 2, 4, 6, and 8 inches in diameter declined (fig. 22). There were relatively small increases in numbers of trees in the larger diameter classes. Apparently, farmers are marketing large shortleaf pine trees and making relatively little effort to regenerate this species.

Numbers of shortleaf pines 2, 4, and 6 inches in diameter also declined on the lands of miscellaneous-private owners (fig. 23). Numbers of trees 10 to 14 inches in diameter increased slightly. It appears that these owners also are marketing large shortleaf pines and making relatively little effort to regenerate this species.

A relatively small decline in the number of 2- and 4-inch shortleaf pines occurred on forest-industry lands. This decline may be explained by a tendency to plant loblolly pine on areas from which shortleaf pine has been harvested. There was a small increase in the number of shortleaf pines between 6 and 14 inches in diameter (fig. 24).

On National Forest lands there was no important change in the number of shortleaf pines in any diameter class (fig. 25). Because of the relatively small land area involved, there is little opportunity to dramatically increase softwood supplies by increasing the amount of shortleaf pine on National Forest lands in Mississippi.

5.5.3 Slash Pine

Slash pine was planted on many acres in south Mississippi prior to 1967. Since 1967 the rate of planting of slash pine has declined in all classes of ownership. The effect of this reduced rate of planting is indicated on the stand charts for NIPF (fig. 26). In 1977 the number of slash pines less than 6 inches was considerably less than in 1967. There was an increase in the number of slash pine trees between 8 and 18 inches in diameter and an associated increase in growing-stock volume. Because of the reduced rate of planting, slash pine in Mississippi will make a minor contribution to ingrowth and growing-stock volumes of softwoods after 1980.

5.5.4 Longleaf Pine

Longleaf pine has not been a favored species for planting or for natural regeneration in past years. Recently some landowners—notably the National Forests—have taken an interest in maintaining longleaf pine stands. Even so, the number of longleaf pine trees continues to decline (table

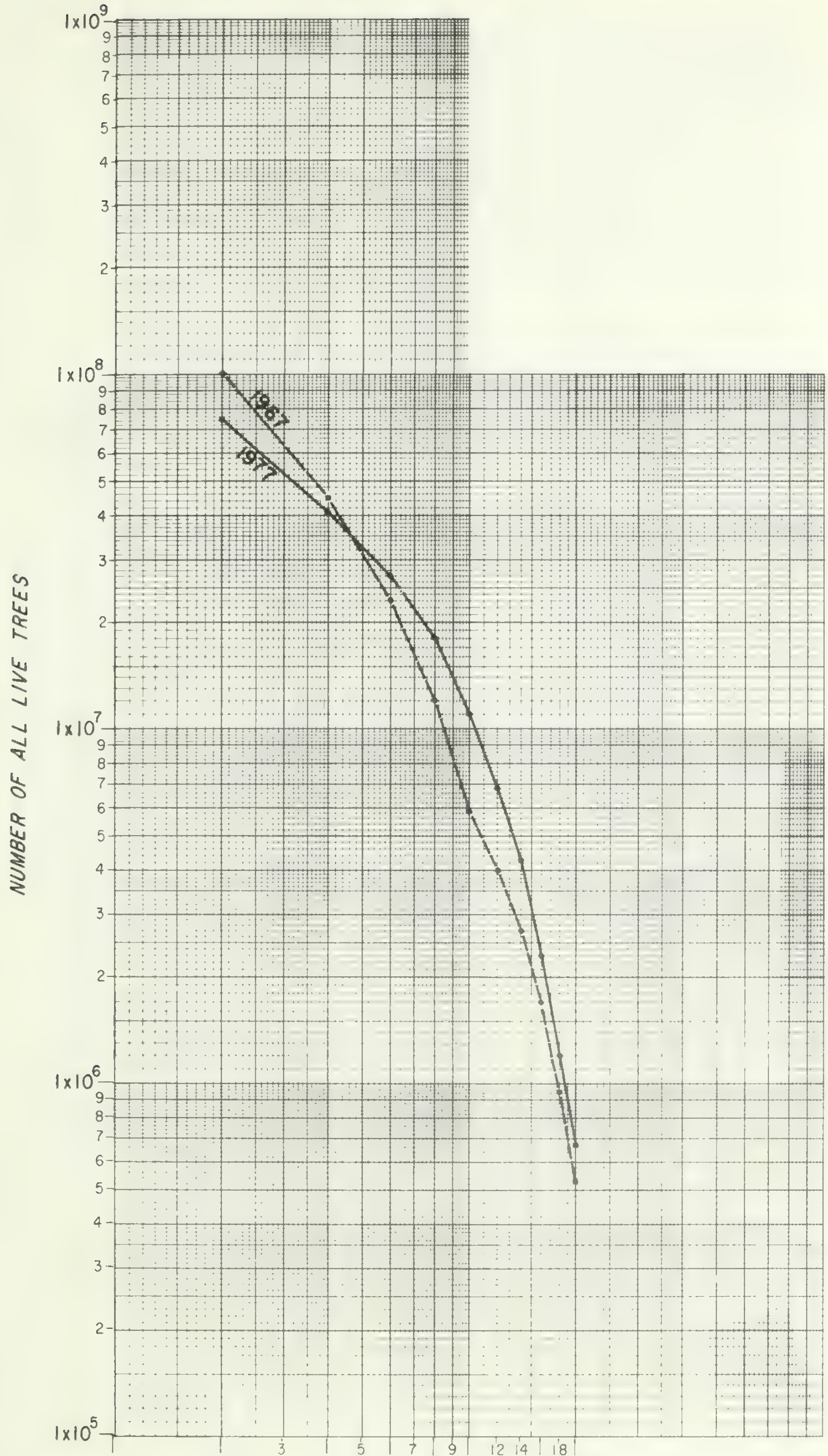

Figure 19.—Distribution of all live loblolly pine trees, by diameter class, on miscellaneous-private ownerships in Mississippi, 1967, 1977.

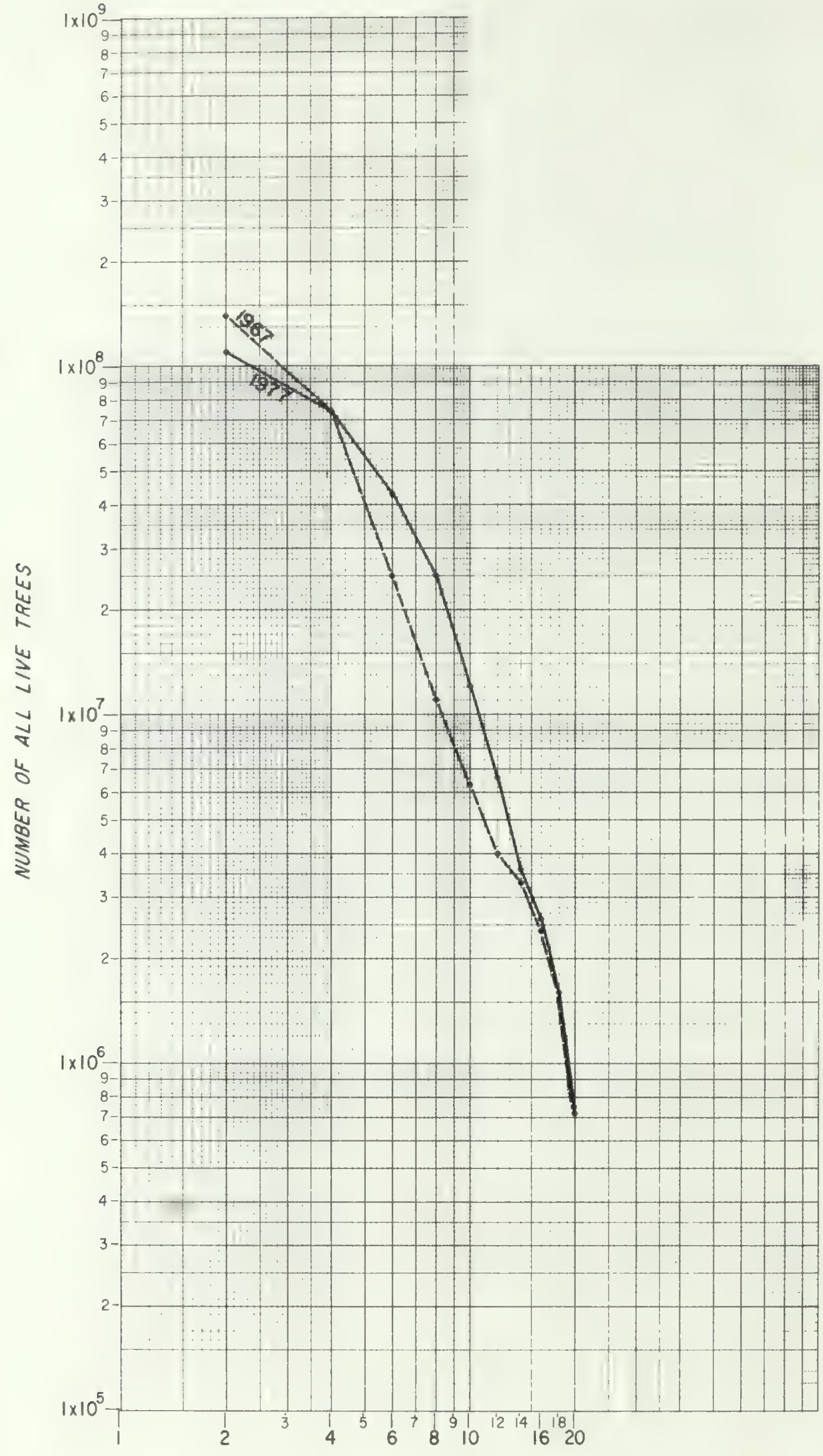

Figure 20.—Distribution of all live loblolly pine trees, by diameter class, on forest-industry ownerships in Mississippi, 1967, 1977.

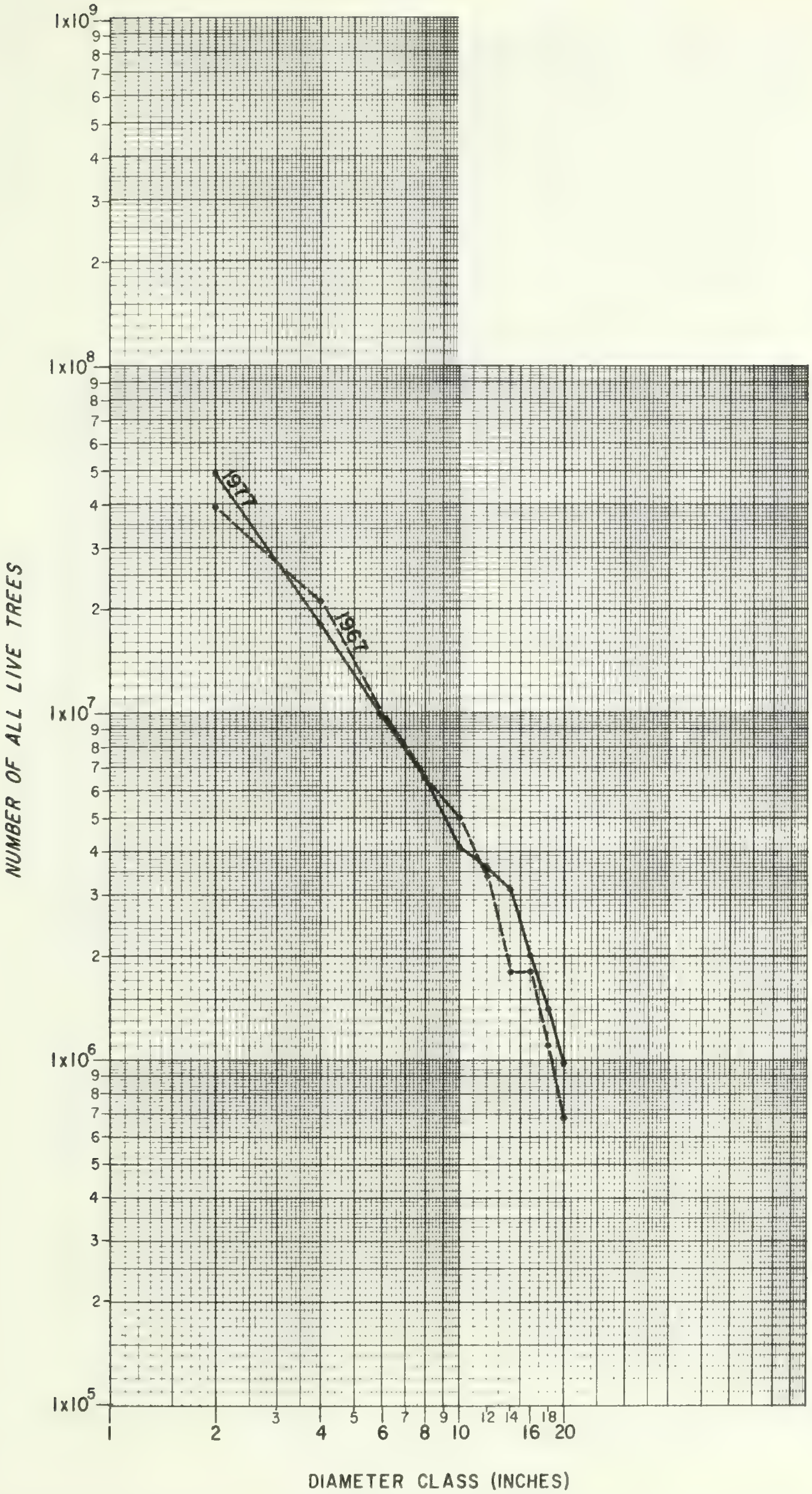

Figure 21.—Distribution of all live loblolly pine trees, by diameter class, on National Forest lands in Mississippi, 1967, 1977.

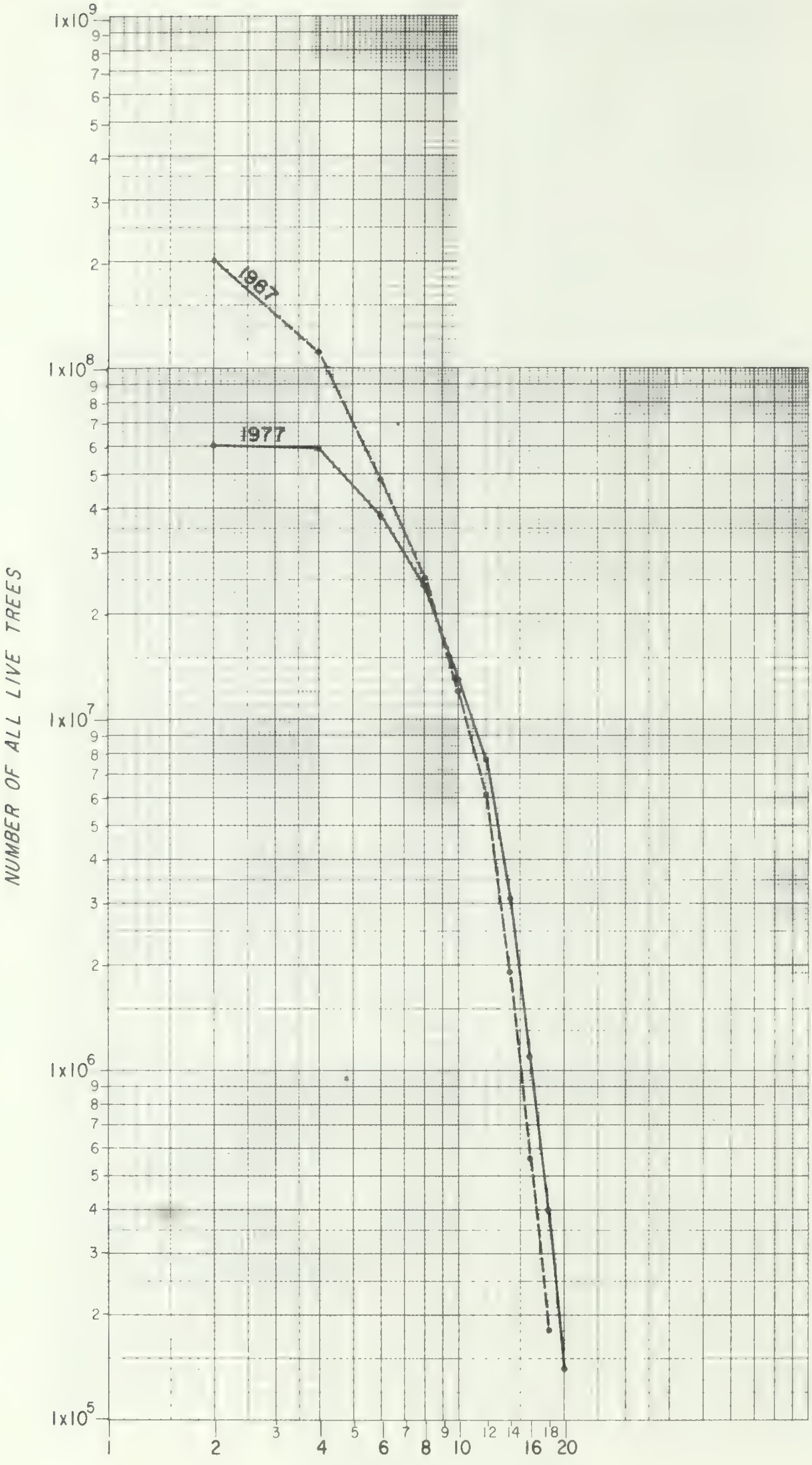

Figure 22.—Distribution of all live shortleaf pine trees, by diameter class, on farmer ownerships in Mississippi, 1967, 1977.

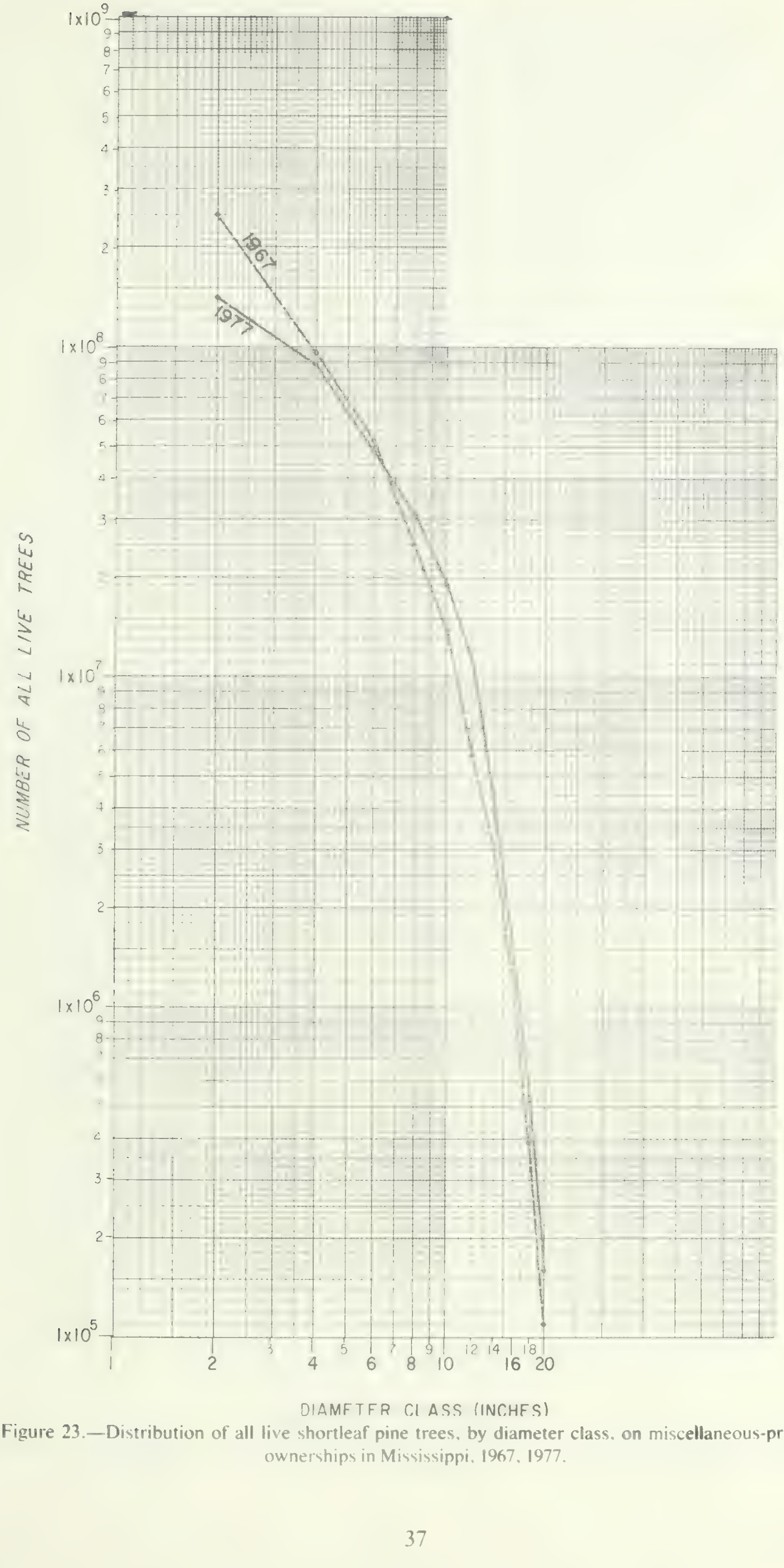

Figure 23.—Distribution of all live shortleaf pine trees, by diameter class, on miscellaneous-private ownerships in Mississippi, 1967, 1977.

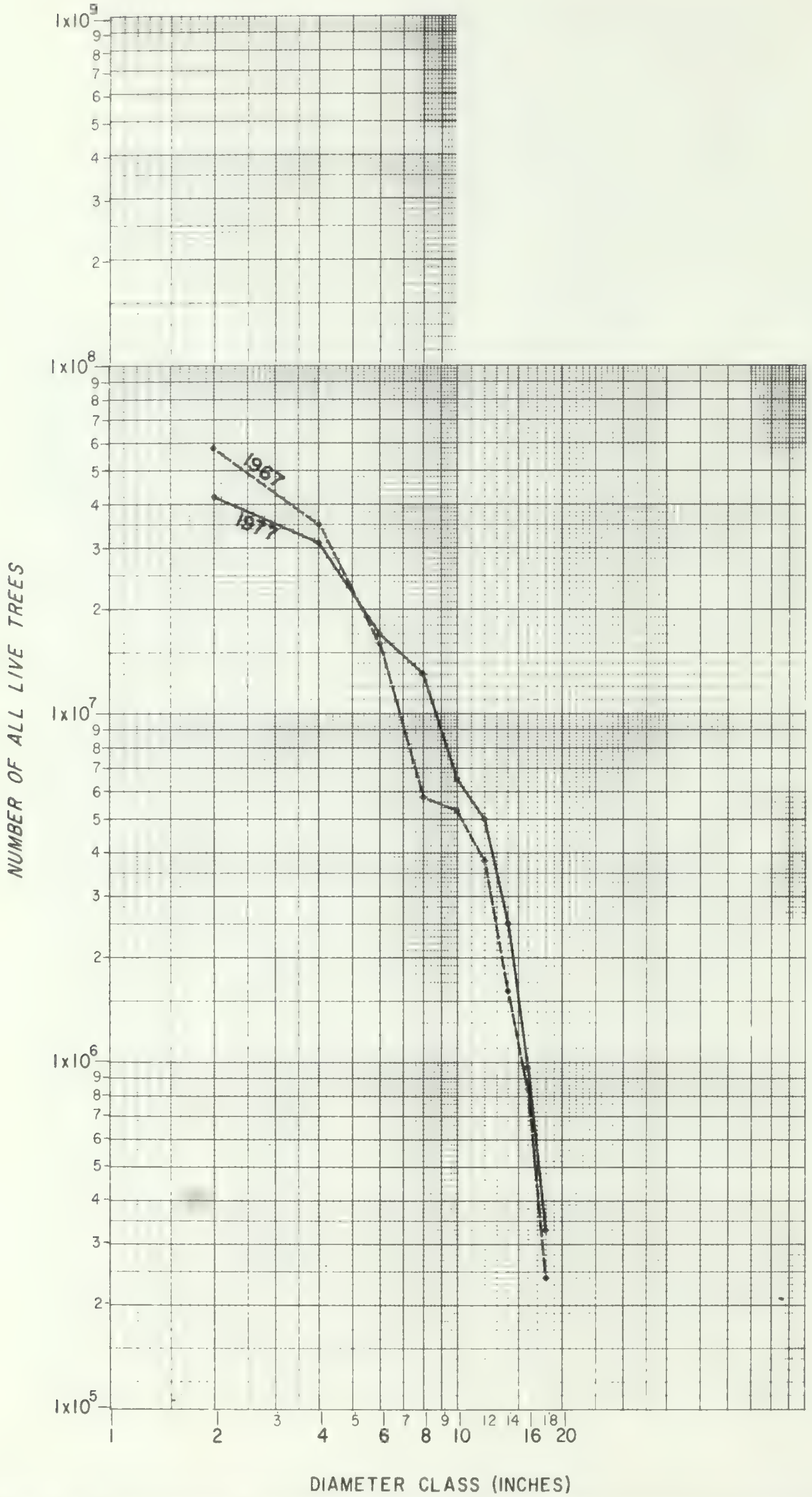

Figure 24.—Distribution of all live shortleaf pine trees, by diameter class, on forest-industry ownerships in Mississippi, 1967, 1977.

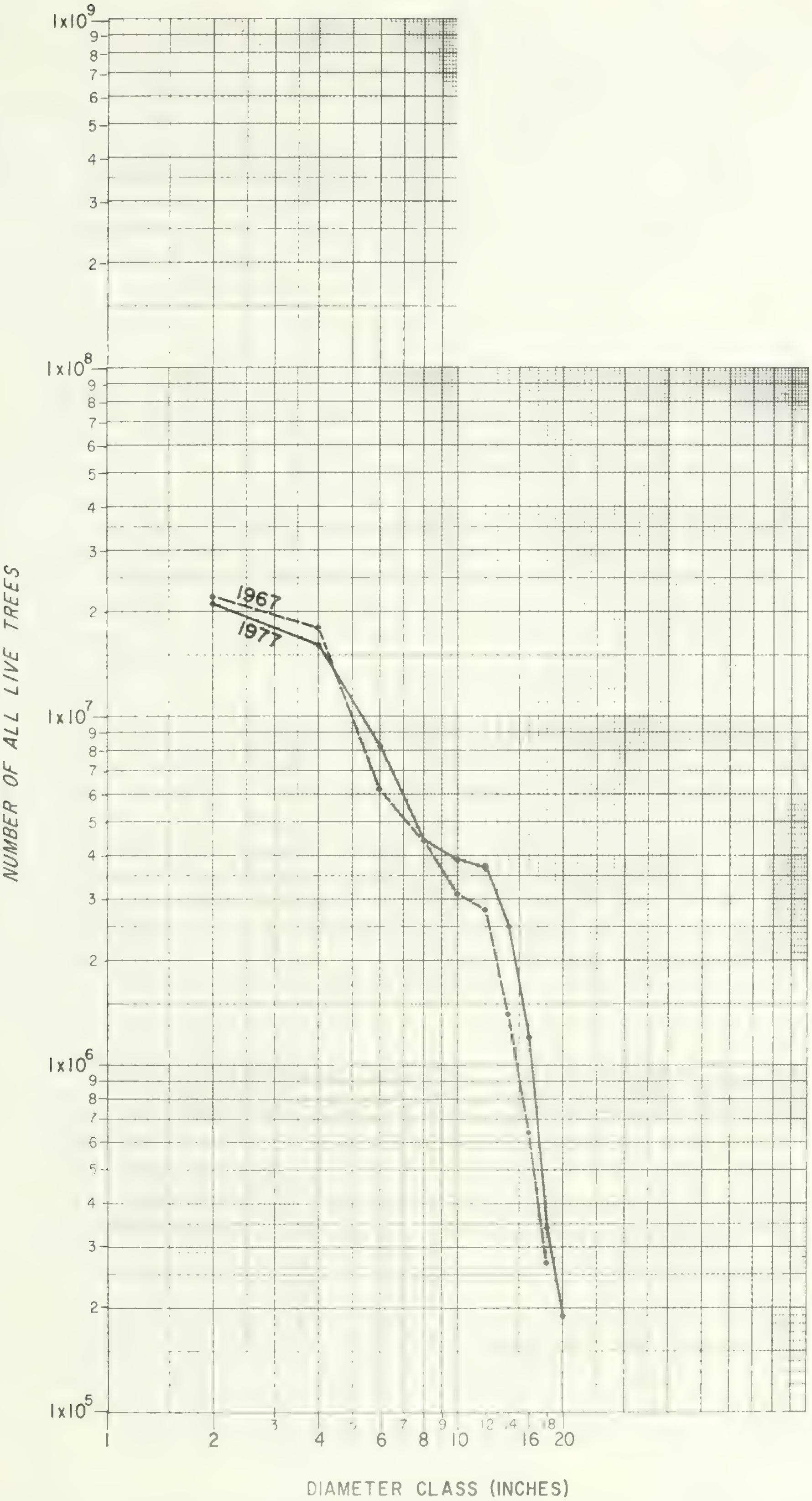

Figure 25.—Distribution of all live shortleaf pine trees, by diameter class, on National Forest lands in Mississippi, 1967, 1977.

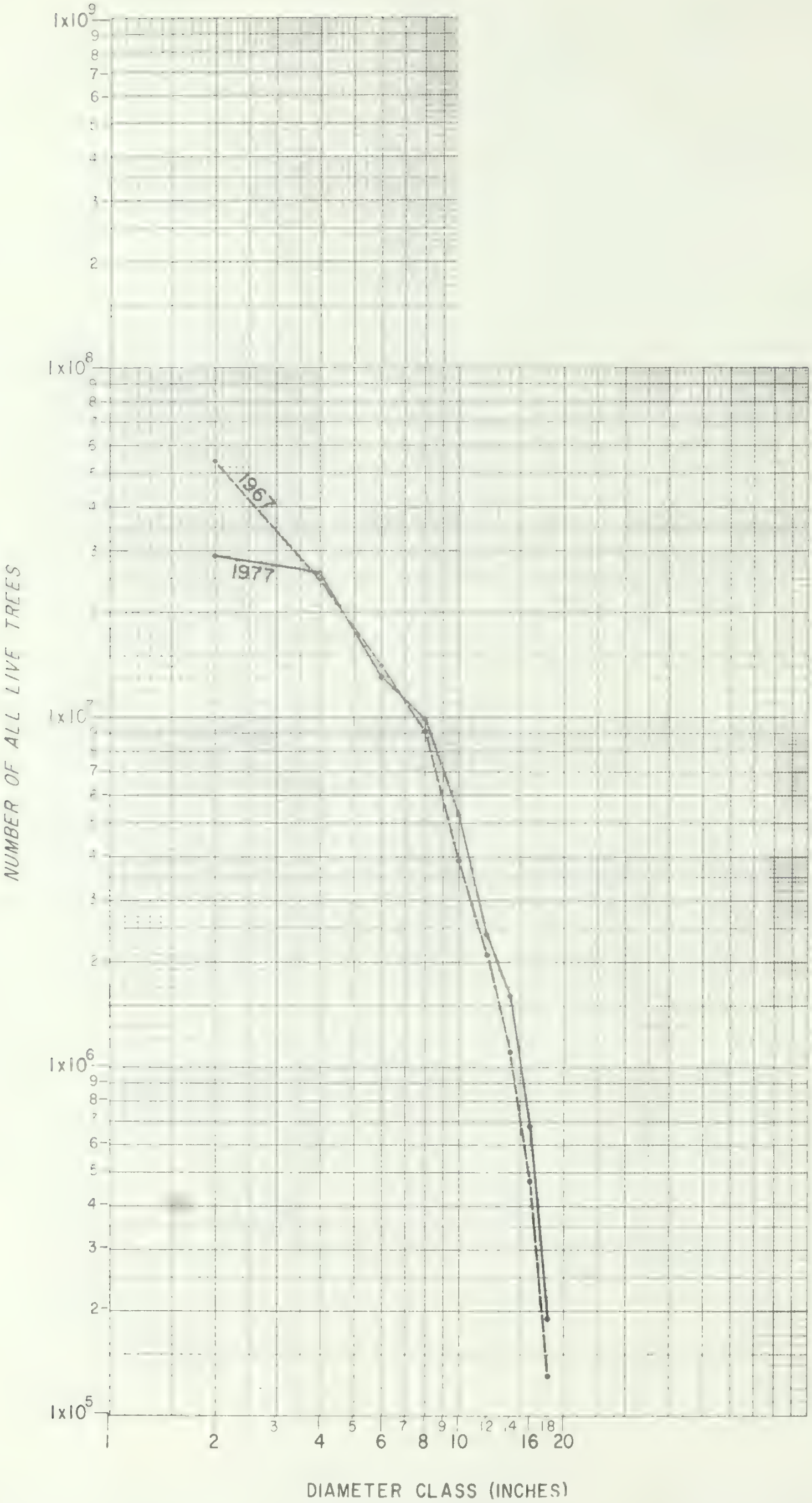

Figure 26.—Distribution of all live slash pine trees, by diameter class, on NIPF ownerships in Mississippi, 1967, 1977.

19). The decline is in the 2- and 4-inch-diameter classes, as for loblolly, shortleaf, and slash pine.

5.5.5 Implications From the Mississippi Data

The number of the live loblolly, shortleaf, slash, and longleaf pines in Mississippi declined by more than 478 million trees between 1967 and 1977 (table 19). The decline was primarily in trees 2 to 8 inches in diameter. The decline is due to reduced rates of regeneration since 1965. During this period, the number of 10-inch and larger trees increased because of the rapid rates of regeneration prior to 1965.

The lowest rates of regeneration occurred on lands owned by farmers, who control 27 percent of all the loblolly and shortleaf pines in Mississippi. The next lowest rate of regeneration occurred on the miscellaneous-private lands, which include 45 percent of all the loblolly and shortleaf pines in Mississippi. Thus, rates of regeneration are lowest on NIPF, which contain most of the State's pine forest. This decline on NIPF lands, therefore, is very significant.

The relatively small acreages in forest-industry and National Forest ownerships are inadequate to compensate for the losses in pine ingrowth from NIPF holdings. For example, forest industry and National Forests combined hold 28 percent of the loblolly pine trees. Even if pines were always regenerated after harvests on these lands, the increase in yields could not compensate for the declines occurring on NIPF. The reduced rate of regeneration on NIPF ownerships, the reduced ingrowth, and the reduced number of 6- and 8-inch trees can be expected to reduce future growing-stock volumes.

5.6 Regeneration of Loblolly and Slash Pines in South Carolina

The fifth inventory for South Carolina was completed in 1978. These new data support the findings reported for Mississippi.

5.6.1 Loblolly Pine

As in Mississippi, NIPF lands contain most of the commercial forest, and loblolly and slash pines are the most important softwood species for timber production (Boyce and others 1975a, 1975b).

In the entire State, numbers of 2-inch loblolly pines on NIPF lands declined by more than 123 million trees (figs. 27, 28, 29). The largest decline was in the Northern Coastal Plain, where numbers of 4-inch trees also dropped. Statewide, the number of 4-inch trees in NIPF declined more than 56 million trees. The number of 6-inch trees increased by about 26 million trees, mostly on the Piedmont Plateau.

Ingrowth from the large numbers of 2- and 4-inch trees found in the inventories in 1957 and 1967 continues to increase the growing-stock volumes for loblolly pine (figs. 27, 28, 29). If future harvest is primarily from trees larger than 10 inches in diameter, growing-stock volumes could continue to increase for at least another decade. However, reductions in the numbers of trees, progressing from the 6-inch to the larger diameter classes, will eventually reduce the growing-stock volumes on NIPF.

5.6.2 Slash Pine

Prior to 1960, slash pine was planted on many areas beyond this species' natural range (Boyce and others 1975b). After 1960 fewer slash pines were planted. This change in planting is observed in the data gathered in 1967 and 1978 (figs. 30, 31). The number of 2-inch trees in 1967 was about equal to the number of 4-inch trees. Although slash pine was still planted between 1967 and 1977, the rate of planting continues to decline.

The reduced rates of planting caused a large reduction in the number of 4-inch trees by 1977 (figs. 30, 31). The number of 6-inch trees was about the same as in 1967. However, the number of trees in the larger diameter classes continued to increase and increase the growing-stock volume. This increase in volume results from the large number of slash pines planted prior to 1960.

Slash pine in the South Carolina Coastal Plain is likely to be a minor source of softwood timber after 1980.

5.7 Significance of a Period of Reduced Rates of Ingrowth

The South is already 14 years into a period (1965–1979) when rates of regeneration are much lower than before 1965. In the next decade, this lower rate of regeneration will cause a smaller number of softwoods to enter the 6-inch-diameter class than entered that class in the previous decade. Over the next few decades, this decline will appear in the larger diameter classes and in total volumes of pine.

Slash pine data from South Carolina provide

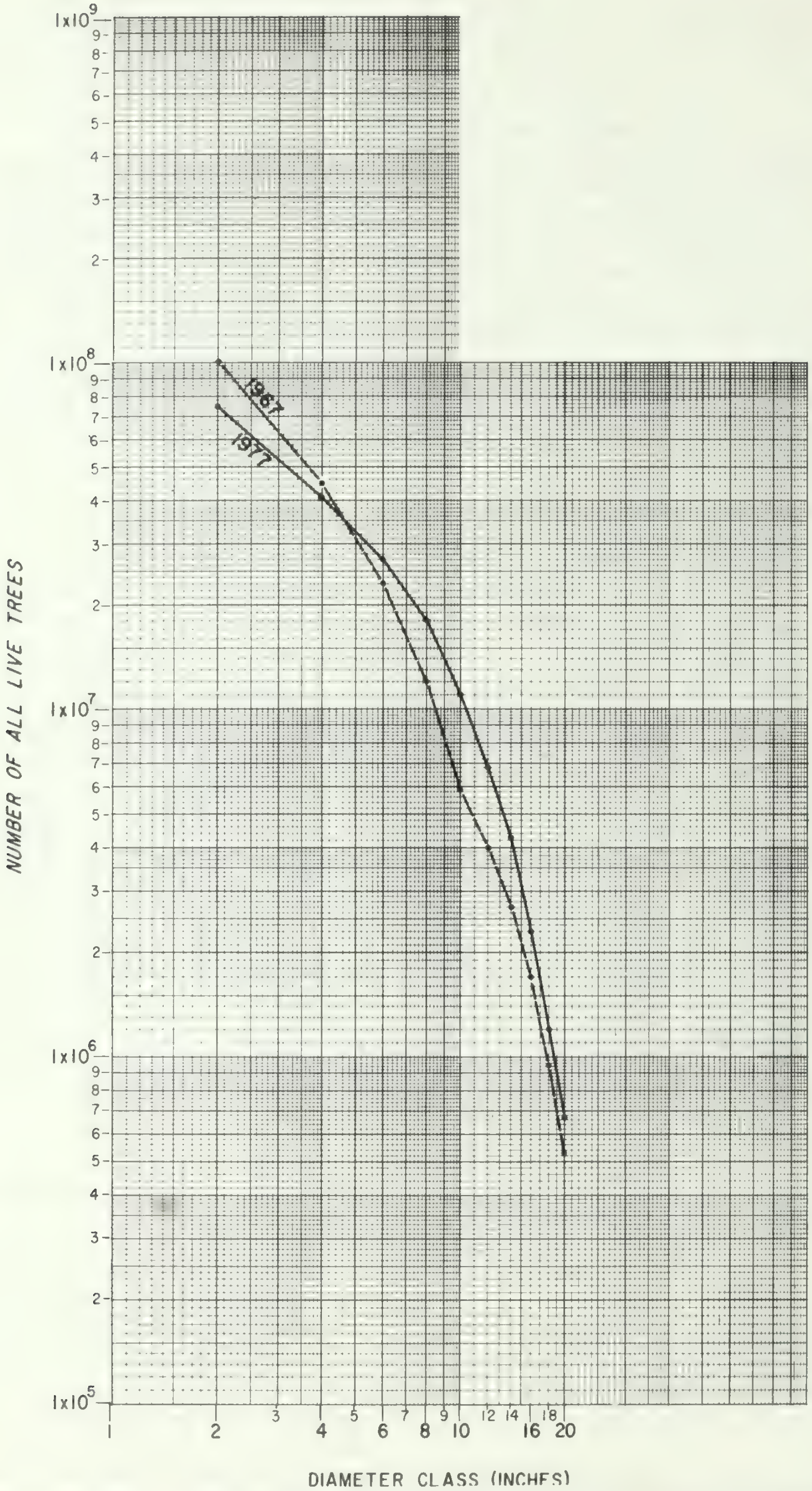

Figure 27.—Distribution of all live loblolly pine trees, by diameter class, in the Southern Coastal Plain of South Carolina, 1967, 1977.

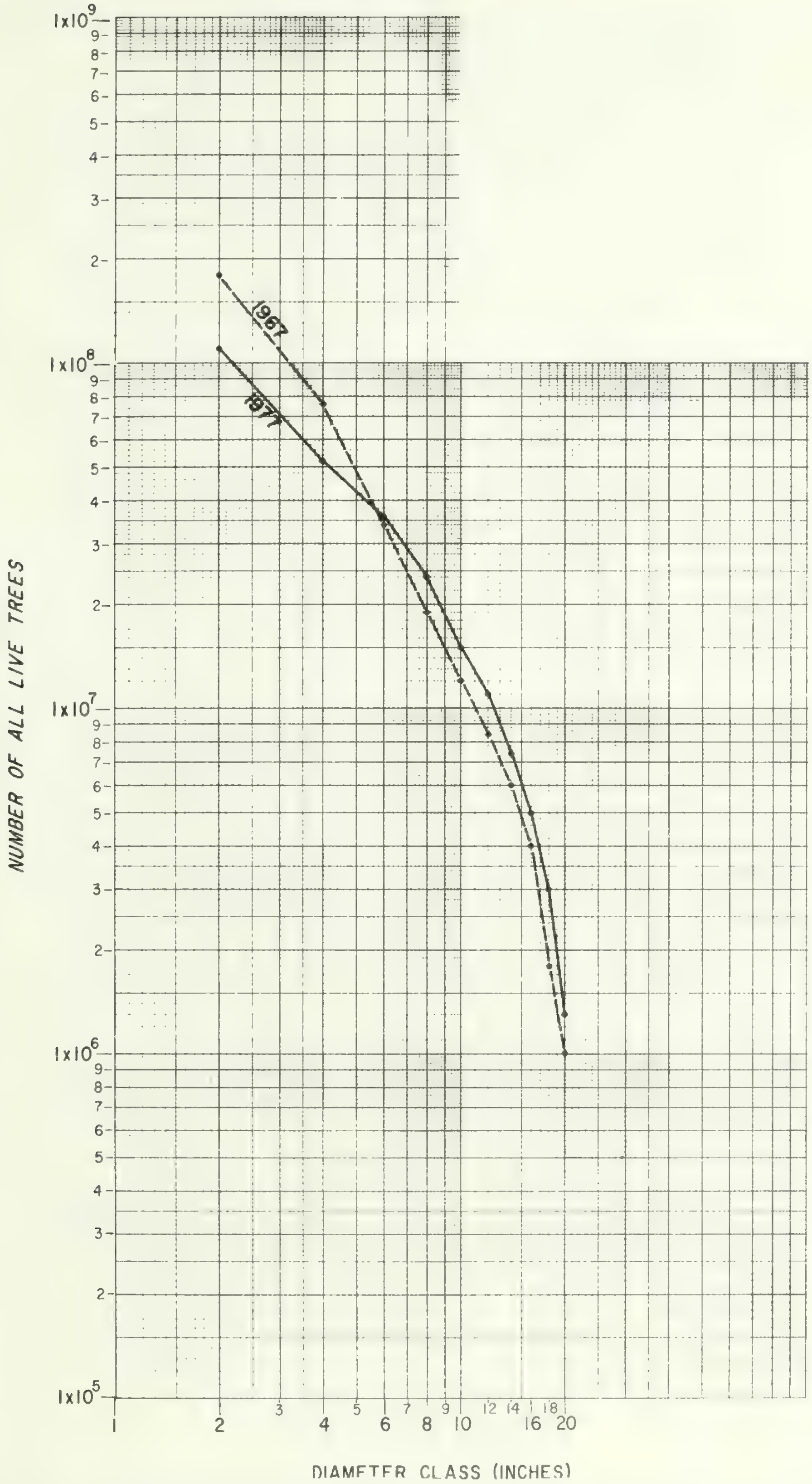

Figure 28.—Distribution of all live loblolly pine trees, by diameter class, on NIPF ownerships in the Northern Coastal Plain of South Carolina, 1967, 1977.

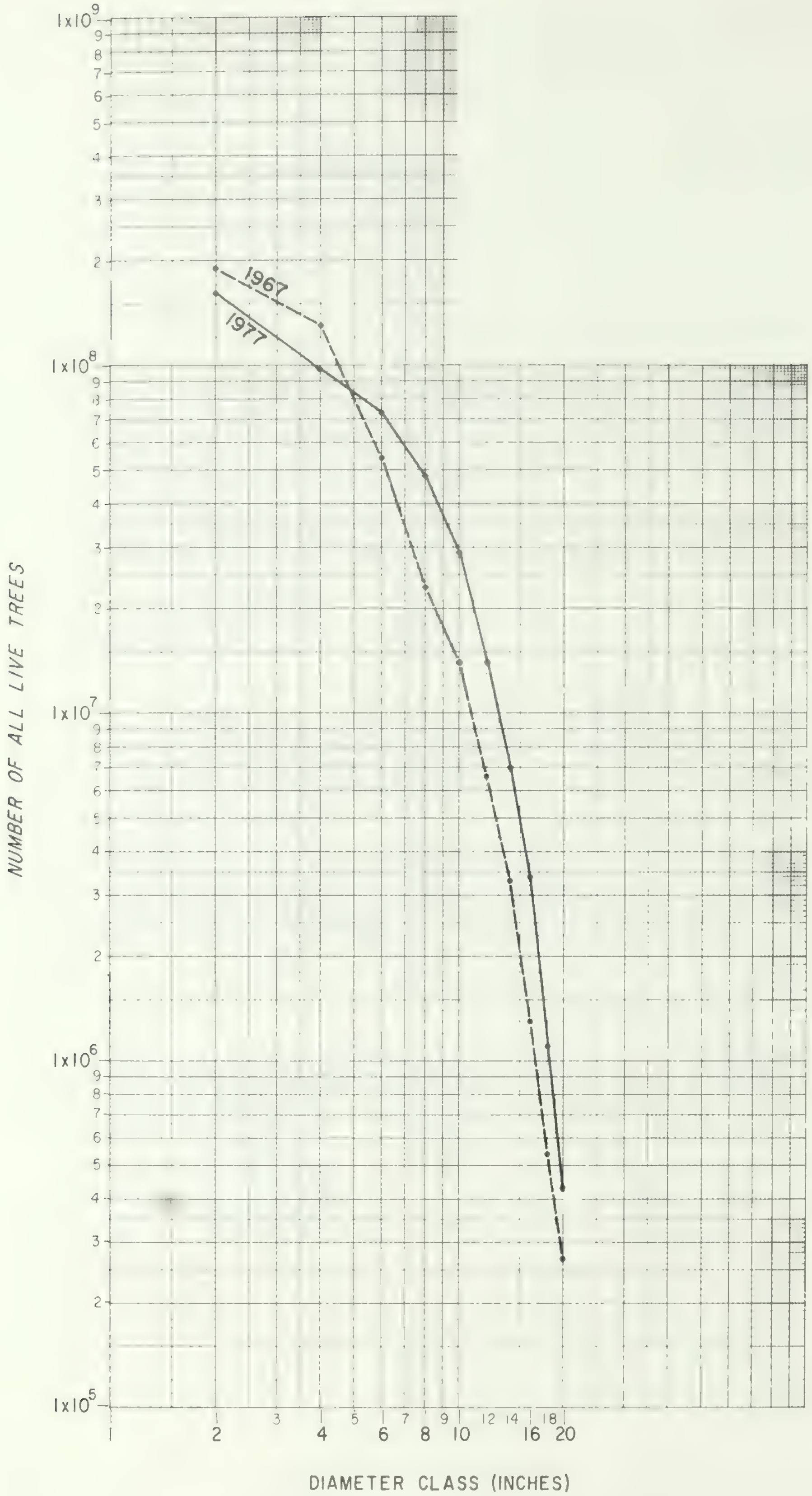

Figure 29.—Distribution of all live loblolly pine trees, by diameter class, on NIPF ownerships in the Piedmont of South Carolina, 1967, 1977.

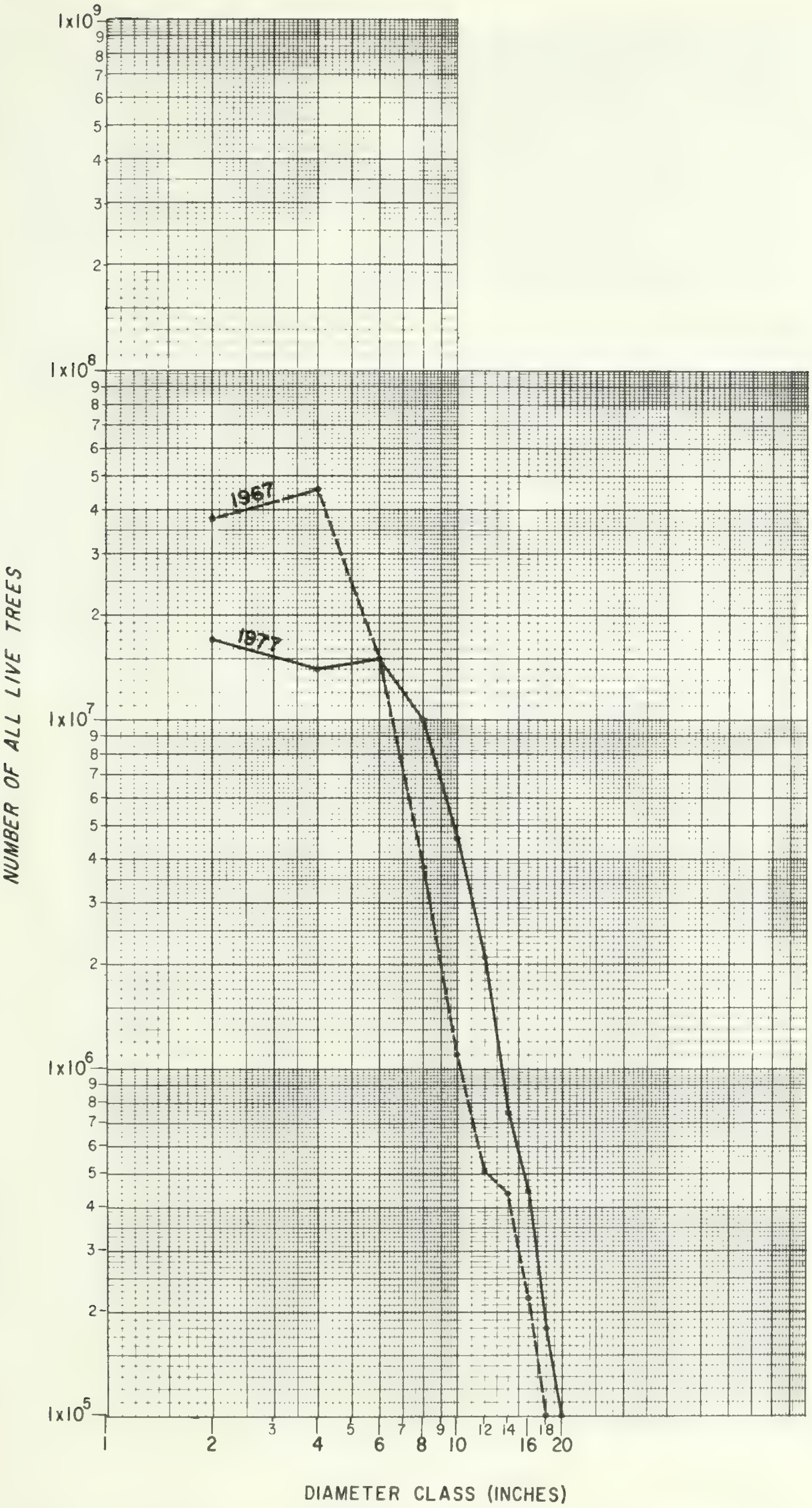

Figure 30.—Distribution of all live slash pine trees, by diameter class, in the Southern Coastal Plain of South Carolina, 1967, 1977.

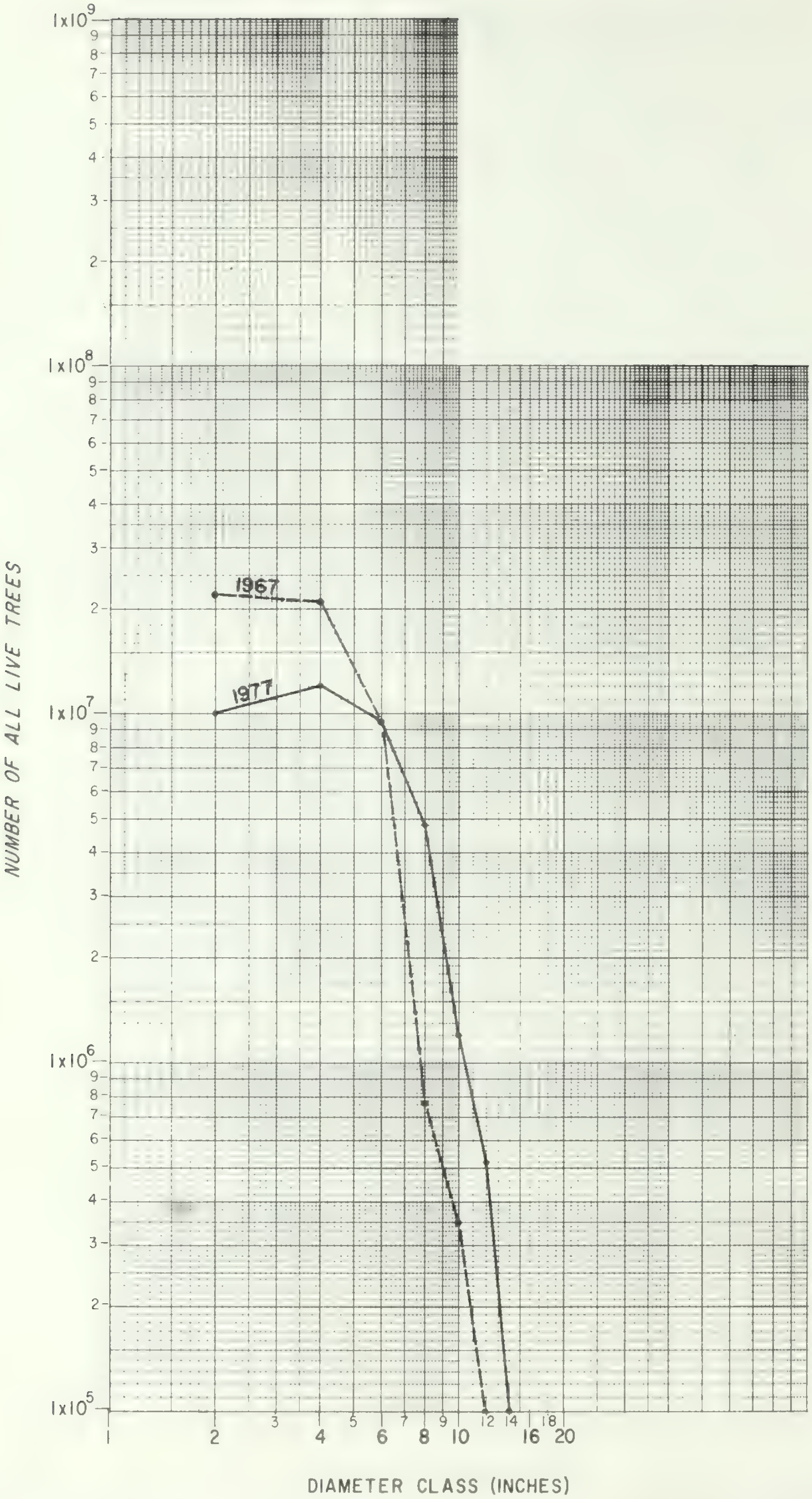

Figure 31.—Distribution of all live slash pine trees,by diameter class, in the Northern Coastal Plain of South Carolina, 1967, 1977.

the best possible demonstration of the thesis of this Paper. Since virtually all slash pines in this State were planted, we can consult annual records for acreages of regeneration. It is beyond doubt that acreages containing slash pine regeneration began to decline in 1960. Nevertheless, almost 20 years later inventories were still recording increases in volume of the species.

Examination of figures 30 and 31 leaves no doubt that these increases cannot continue. If harvesting continues at a normal pace, total volume will begin to decline very soon if it has not done so already.

And if the effects of failure to regenerate pines take 15 to 20 years to show up in volume totals, so do the positive effects of efforts to increase regeneration rates. Even if the rate of slash pine regeneration were suddenly increased, the relatively low number of trees now less than 6 inches in diameter would result in reduced numbers of larger trees for a long period.

The example of the effects of reduced slash pine planting in South Carolina is not meant as a plea to increase planting of this species in this State. Rather, it is meant to demonstrate what is happening with all southern pine species in all Southern States.

These effects (reduced ingrowth and reduced growing-stock volumes), initiated by the 14-year period of reduced rates of regeneration, cannot be changed immediately by increasing rates of regeneration. Trees planted now would not add to growing-stock volumes until the number of trees in the 6- to 10-inch-diameter classes increased. Such an increase would be expected about 20 years after planting the trees. Another 10 years would be required for an increased number of trees to move into the 12-inch and larger diameter classes and thus make important contributions toward increasing softwood roundwood supplies.

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Boyce, Stephen G., and Herbert A. Knight.

1979 Prospective ingrowth of southern pine beyond 1980. U. S. Dep. Agric. For. Serv., Res. Pap. SE-200, 50 p. Southeast. For. Exp. Stn., Asheville, N.C.

Between 1980 and 1990 the prospective ingrowth from 2- and 4-inch softwood trees to larger trees will be smaller than before 1974. This decline in rate of ingrowth will reduce the number of pines in the 6-inch and larger diameter classes, especially on the nonindustrial private forests. The most important action for increasing ingrowth and the future harvests of southern pines is to reestablish pines on lands when mature pines are harvested. Growing stock volumes cannot be expected to increase until 20 to 30 years after the rate of regeneration is increased.

KEYWORDS: Southern pine, ingrowth, pine regeneration.

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COM-PLY® REPORT 17

ECONOMIC FEASIBILITY OF MANUFACTURING COM-PLY PANELS IN THE SOUTH

COOPERATIVE RESEARCH

COM-PLY is a registered trademark of the American Plywood Association.

December 1979

Southeastern Forest Experiment Station
Asheville, North Carolina

Economic Feasibility of Manufacturing Com-ply Panels in the South

by

Gerald A. Koenigshof, Research Scientist
Forestry Sciences Laboratory
Athens, Georgia

Cooperative Research by
U.S. Department of Agriculture, Forest Service
Southeastern Forest Experiment Station
and
U.S. Department of Housing and Urban Development
Division of Energy, Building Technology
and Standards

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing was initially limited to COM-PLY studs but has now been extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this was not a temporary problem and that long-range plans for better using the Nation's available forest resources would be necessary.

The Forest Service of the U.S. Department of Agriculture and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of COM-PLY studs and joists is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall and floor framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs and joists. Other reports will describe the overall project, compare the strength of composite and solid wood lumber, suggest performance standards for composite lumber, and provide construction details on houses incorporating such lumber. Still others will explore the economic feasibility of manufacturing composite lumber and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

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Economic Feasibility of Manufacturing Com-ply Panels in the South

Abstract.—Investments, production costs, and probable returns for manufacture of COM-PLY panels in the South are presented. It is possible to obtain a 20 percent or greater after-tax internal rate of return on an investment in manufacturing COM-PLY panels. This study shows that a manufacturing system that assembles the panels in two stages is more economic than a system that assembles the panels in a single stage.

KEYWORDS: Manufacturing costs, sheathing cost, economics of panel manufacture, cost analysis, plywood costs.

Cooperative research by the Forest Service, U.S. Department of Agriculture, and the U.S. Department of Housing and Urban Development has led to development of a new composite panel product. The new product, called COM-PLY, has potential for significantly increasing our supply of sheathing for building homes. COM-PLY panels are intended to be direct substitutes for plywood panels now widely used for roof and floor sheathing. COM-PLY panels are a structural sandwich construction with a 0.3-inch-thick particleboard core placed between 0.1-inch-thick layers of solid wood veneers (fig. 1). The first composite panel products developed were roof and floor sheathing. Information on performance of these panels is summarized in COM-PLY Report 3 (Carney 1977).

COM-PLY panels need to be priced competitively with plywood so builders will have incentive to purchase them. Potential manufacturers of COM-PLY panels want to know how much it will cost to manufacture COM-PLY panels. They also want to know if a COM-PLY panel factory would be a profitable investment, one that would have a greater rate of return on the investment than a plywood factory. This report presents estimates on the amount of investment required to build a particleboard, veneer, and panel-laminating factory; the annual sales and cost of manufacturing COM-PLY panels and operating cash flows; and the annual net cash flows and internal rate of return.

Any financial feasibility study is only as good as the assumptions upon which it is based. In this study, we assumed that the factory would be located in Arkansas and would use southern pine wood. The assumptions concerning costs are based on industry averages and therefore do not reflect values for any specific company.

Results presented in this report do not guarantee that any firm can profitably manufacture COM-PLY panels—profitability depends on competent managerial skills, market demand, production efficiency, and other business factors. The results strongly indicate that it is economically feasible to manufacture COM-PLY panels. Although a specific firm's price, assumptions about cost, and quantity may vary from those assumed in this report, minor variances would not affect the overall conclusions reported. Companies contemplating the manufacture of COM-PLY panels should substitute their own local cost estimates in a similar analysis to check economic feasibility for their particular location.

FINANCIAL FEASIBILITY ANALYSIS

PROCESSES USED FOR MANUFACTURE

Feasibility of any manufacturing venture is greatly affected by the processes used. In this report, two methods of production are analyzed. In the first method, referred to as Case I, a prepressed mat of wood particles coated with

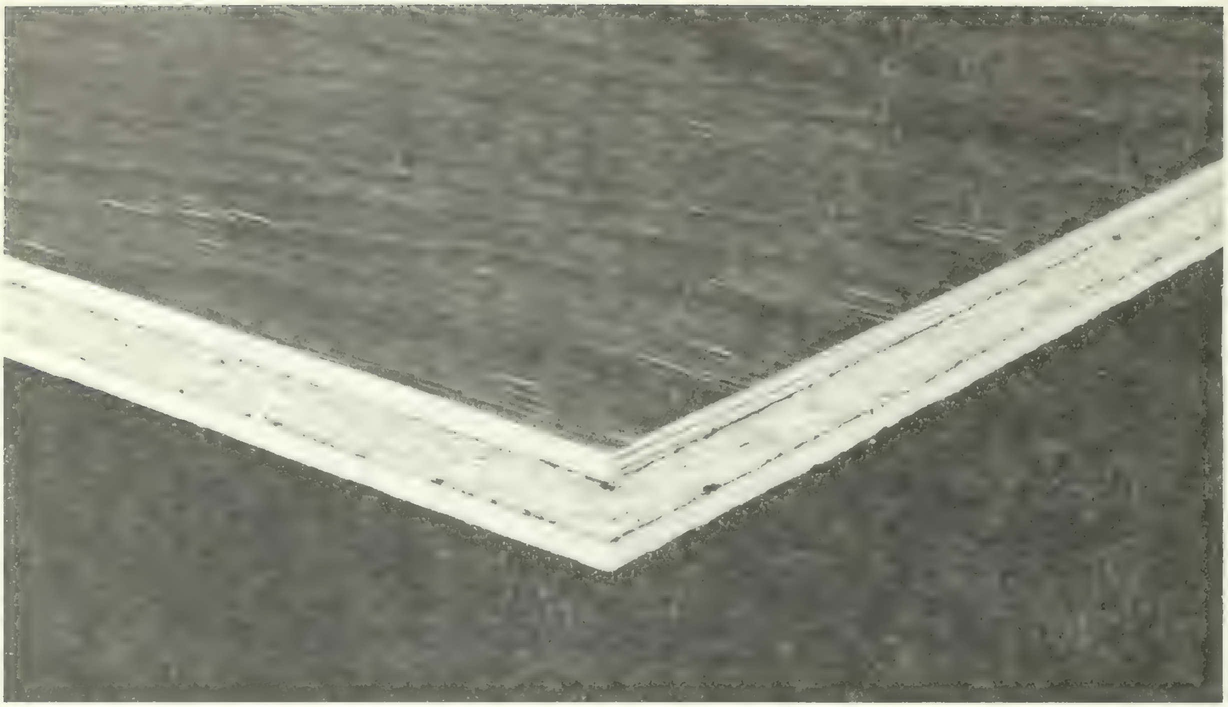

Figure 1.–COM-PLY panel used for sheathing roofs of houses.

resin is placed between two sheets of veneer. A number of these veneer-mat assemblies are loaded into a high-pressure multiplaten hot-press to cure the resin in the flakeboard and bond the veneer to the flakeboard in a single stage. In the second method, Case II, 4- by 8-foot flakeboard panels are made by the conventional methods for manufacturing particleboard. Then, these flakeboard panels are placed between two sheets of veneer and the veneer is bonded to the flakeboard in a conventional low-pressure plywood press, using conventional plywood glue. Case II is a two-stage operation and requires a particleboard press line and a panel press line. Panels made by Case I and Case II methods are identical.

Process for Case I

Veneer blocks are debarked, steamed, and rotary cut as they would be in a plywood plant. The veneer is clipped, dried, and graded in much the same manner as veneer for plywood. Unlike plywood, however, COM-PLY panels do not have veneer crossbands. Since all veneer is used as panel facings, equipment must be available to edge-bond narrow strips of veneer into sheets wide enough for panel facings.

The peeling residues (core, roundup, and block trim) and the portions of pine stems too small or crooked for peeling are used to make flakes for the flakeboard core of COM-PLY panels. The peeler cores are fed endwise through a rotary flaker which shaves the peeler core into flakes much like a huge pencil sharpener. The ideal flake is 0.19 to 0.31 inch wide, 1.25 to 1.75 inches long, and 0.02 to 0.03 inch thick. Flakes wider than 0.31 inch may curl, making them difficult to coat uniformly with resin during the blending operation. The flakes need to be 3 to 7 times longer than they are wide because the flakes must be oriented with their grain across the COM-PLY panel. Processes for orientating flakes either mechanically or electrically require flakes that are longer than they are wide. High-quality flakes of the type just described should make up about 60 percent of the furnish in the flakeboard. The remaining wood particles can come from bark (not more than 5 to 7 percent of the board) or other forest and mill residues. Some fine material and particles not having the ideal shape can be used.

Particles can be oriented at low cost. To understand the process, visualize a toothpick dropped into a piece of paper with a V-shaped fold. The toothpick aligns itself in the direction of the V-groove. Other particles also will do so if they are longer than they are wide. Next, visualize a cylinder with its longitudinal axis in a horizontal position and having V-grooves on its circular surface. Wood particles are dropped onto the cylinder and align themselves in the V-grooves. As the cylinder turns, the particles are dumped out to form a mat whose particles are aligned in the direction of the V-grooves on the cylinder. Other operations such as blending, forming, and prepressing are very similar to well-known methods of particleboard manufacture. Sheets of face veneer approximately 54 by 102 inches are passed under the forming stage, and a mat of oriented flakes that has been blended with resin and wax is laid on top of the veneer. Then, a second sheet of veneer is placed on top of the mat. This veneer-mat assembly must be pre-pressed and hot-pressed. A disadvantage of this process is that long press times are required to heat through both the veneer and the flakeboard assembly. Finishing operations, such as panel patch, plug, trim and sanding if required, are similar to those used for making plywood.

Process for Case II

Veneer processing, flake preparation, and finishing of panels are the same as for Case I. For Case II, 4- by 8-foot flakeboard panels are made in a standard multiplaten particleboard hot-press. These panels have the flakes oriented with their lengthwise direction across the panel (in the 4-foot direction) as in Case I. For a 1/2-inch-thick COM-PLY panel, the flakeboard is 0.3 inch thick and will have two 0.1-inch-thick veneer facings added to it in a subsequent stage. An advantage of the Case II method is the short press time for flakeboard cores. After the flakeboard panels are made, veneer is glued to each face with standard plywood adhesive in a multiplaten plywood hot-press. A glue spread rate of 40 lb/Mft^2 of glueline is used. This operation is faster than making plywood panels for two reasons. First, the press cycle is short because only the face veneers must be heated hot enough to cure the glue. In making plywood, heat must penetrate to centrally located gluelines. Second, the veneer-core layup operation can be easily automated for rapid assembly. Layup of crossbands in plywood is slow and difficult to automate.

INVESTMENT REQUIREMENTS

Land

A COM-PLY panel plant would require about 30 acres, and land cost was assumed to be $8,950 per acre. Thus, total land cost would be $268,500. Land-developing costs for such things as engineering, overhead, and contingencies were assumed to be $51,000. Thus, the total cost of land and development is $319,500.

Buildings

A main building with 150,000 square feet, constructed at a cost of $8.40 per square foot, and miscellaneous small buildings with 7,000 square feet, constructed at a cost of $10.98 per square foot, would be required in Case I. Costs would be $1,260,000 and $76,900 for these structures. For Case II, a main building with 170,000 square feet and miscellaneous small buildings with 10,000 square feet are required. The structures for Case II would cost $1,428,000 and $109,800, respectively. Engineering design, construction overhead, and contingencies add $500,000 to the basic building cost for each case, and total costs for buildings are $1,836,900 for Case I and $2,037,800 for Case II.

Facilities

Cost of facilities to be added to the buildings and grounds in order to make the factory operational are:

Facility	Cost Case I (dollars)	Cost Case II (dollars)
Site preparation	30,000	30,000
Roads, parking, and paving	30,000	30,000
Outside fire protection	48,000	48,000
Outside lighting	3,600	3,600
Outside piping (water supply and sewer)	12,000	12,000
Waste disposal	6,000	6,000
Fuel storage (gas and diesel tanks and pumps)	6,000	8,000
Inside electrical equipment (installed)	528,000	633,600
Inside piping (air, water, sewer)	43,200	51,800
Engineering, construction overhead, and contingencies	353,400	411,500
Total	$1,060,200	$1,234,500

Machinery

In this study, it was assumed that new machinery was purchased. Table 1 lists machinery and its cost for both Case I and Case II methods of panel manufacture. The number and size of machines required depend on the flow of materials through the factory. A number of choices are available. We chose one combination of machines for each case. Installed cost of machinery is $6,763,050 for Case I and $8,554,100 for Case II. Both Cases I and II use a 4- by 8-foot by 30-opening press for final panel assembly. However, Case I requires a single 30-opening high-pressure press, while Case II uses a low-pressure 30-opening standard plywood press to apply veneers to flakeboard cores and a 4- by 24-foot by 14-opening standard high-pressure particleboard press for making cores. Also, Case II requires two veneer driers to handle the larger flow of veneer associated with that process. Otherwise, the panel-making machinery is the same for both cases.

Cash

In this analysis, we assume that the equivalent of 2 months' payroll is sufficient cash to meet the payroll, provide petty cash, and otherwise meet cash needs to operate the business. In a later section, we show that the annual labor cost in 1975 would be $1,322,184 for Case I and $2,004,168 for Case II if the plant were operating at 100 percent capacity. Thus, cash required was assumed to be $220,364 for Case I and $334,028 for Case II.

Inventory

Investment is required for raw materials, for materials being processed, and for finished products awaiting shipment. In this study, one-sixth of the annual cost of raw materials for a factory operating at full capacity was assumed to be sufficient to cover all requirements for inventory investment. It will be shown that the total annual cost of raw materials for Case I is $3,061,946 and $7,144,221 for Case II. Therefore, the investment required for inventory is $511,344 for Case I and $1,193,085 for Case II.

Accounts Receivable

A considerable investment is required to cover sales to customers who do not pay immediately for the products purchased. These accounts receivable may typically be paid in 10 to 60 days. The average collection period from customer sales was assumed to be 30 days. Investment to cover accounts receivable was considered to be 1 month (30 days) of sales. Sales will vary with the unit price received for products and the quantity produced each year. In this study, we used average 1975 prices of $\$122/\mathrm{Mft}^2$ for grades C-D unsanded panels f.o.b. mill and $\$231.80/\mathrm{Mft}^2$ for A-B sanded panels f.o.b. mill. For a product mix of 80 percent C-D panels and 20 percent A-B panels, the volumes produced are 11,696,256 square feet of A-B sanded panels and 46,785,024 square feet of C-D unsanded panels per year for Case I. The accounts receivable for Case I is 1 month of sales, or $701,580. For Case II, the volumes produced per year are 25,344,000 square feet of A-B sanded panels and 101,376,000 square feet of C-D unsanded panels, or a total of 126,720,000 square feet. Accounts receivable for Case II total $1,520,218.

Contingency

The investment for any individual item, such as land or buildings, may vary from the amount assumed, and items not planned for may be required. To allow for such contingencies, we allotted 5 percent of all other investments. The totals of all investments up to this point for Case I are $11,412,938 and $15,193,230 for Case II. Five percent of $11,412,938 is $570,647, which is the contingency investment for Case I. Five percent of $15,193,230 is $759,662, which is the contingency investment for Case II.

Timing of Investments

The time when an investment is made is important in an economic analysis. Cash invested in a factory could have been invested in interest-bearing securities. In this study, we assume that the major capital investments would be made during the first 3 years of factory operation. Table 2 shows the amounts and timing of investments for Case I and Case II. The total investment for a new COM-PLY stud factory is $11,983,600 for Case I and $15,952,900 for Case II.

Table 1.–Machinery and machinery cost for a COM–PLY panel factory

Machinery or associated item	Cost	
	Case I	Case II
	. . . . . . Dollars	
Log storage and handling (unloaders, storage skids, sprinkling facilities)	182,250	182,250
Log-barking equipment	445,000	445,000
Machinery foundations and supports (installed)	187,000	187,000
Block-handling equipment and steam vault	238,000	238,000
Boiler	189,000	189,000
Log conveyors to lathe and foundation (installed)	41,850	41,850
Lathe and charger (installed)	261,900	261,900
Trays and tripples (installed)	75,600	75,600
Green clipper (installed)	96,000	96,000
Green veneer sorting line (installed)	92,000	92,000
Green veneer system belt	7,400	7,400
Green veneer clipper and conveyor (installed)	71,550	71,550
Core chipper (installed)	52,650	52,650
Bark conveyor (installed)	48,600	48,600
Chip-handling facility	48,600	48,600
Dryer(s) (installed)	545,000	1,090,000
Dryer feeder(s)	58,320	116,640
Dryer unloader(s)	34,630	69,760
Moisture meter	6,750	6,750
Dry-sorting chain	13,500	13,500
Dryer emission control equipment	36,450	36,450
Flaker	67,500	67,500
Fiber dryer	472,500	472,500
Fiber dryer emission control equipment	20,250	20,250
Fiber screen	8,100	8,100
Glue mixing, pumping, and metering equipment	22,950	22,950
Blender (installed)	45,000	45,000
Forming felter and caul line	735,000	735,000
Curtain coater	72,000	72,000
Semi-automatic layup system	270,000	270,000
Prepress	55,000	55,000
Particleboard press (4 ft. x 24 ft.–14 openings)		1,525,000
Board cooler and conveyor		162,000
Hot-press (4 ft. x 8 ft.–30 openings, HP)	720,000	
Hot-press (4 ft. x 8 ft.–30 openings, LP)		185,600
Hot-press loading and unloading system	210,000	210,000
Saw line	195,750	195,750
Veneer edge-gluing equipment	103,000	103,000
Veneer plugger	50,850	50,850
Packaging and strapping machine	4,500	4,500
Hog-fuel system	17,550	17,550
Forklifts and carts	90,000	90,000
Air compressor (installed)	50,000	50,000
Maintenance equipment and small tools	67,500	67,500
Sander	130,000	130,000
Sander feeder	20,500	20,500
Conveyor to grade line	5,000	5,000
Panel patch line	54,600	54,600
Patching equipment (pumps, gun, etc.)	10,000	10,000
Spare parts and quality control equipment	70,200	70,200
Sweeper and yard truck	25,650	25,650
Storage banks	80,000	80,000
Storage bins	60,000	60,000
Air conveyors (blowers, cyclones, piping)	126,000	126,000
Freight in for machinery	171,600	171,600
Total	6,763,050	8,554,100

Table 2.–Net investment required for the first 3 years of factory operation for Case I and Case II

Investment	Beginning of first year		End of first year		End of second year		End of third year		Total[1]	
	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II
	Dollars									
Land	319,500	319,500	0	0	0	0	0	0	319,500	319,500
Buildings	0	0	612,300	679,300	1,224,600	1,358,500	0	0	1,836,900	2,037,800
Facilities	0	0	848,200	987,600	212,000	246,900	0	0	1,060,200	1,234,500
Machinery	0	0	2,254,300	2,851,400	4,508,700	5,702,700	0	0	6,763,000	8,554,100
Cash	0	0	73,500	111,300	146,900	222,700	0	0	220,400	334,000
Inventory	0	0	170,400	397,700	170,400	397,700	170,400	397,700	511,300	1,193,100
Accounts receivable	0	0	233,900	506,700	233,900	506,700	233,900	506,700	701,600	1,520,200
Contingency	70,600	59,700	100,000	100,000	150,000	250,000	250,000	350,000	570,600	759,700
Net investment	390,100	379,200	4,292,600	5,634,000	6,646,600	8,685,300	654,300	1,254,400	11,983,600	15,952,900

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[1] Totals may differ from values in columns due to rounding.

FLOW OF MATERIALS

Forest products manufacturers with whom we worked in making this study said that the results would only be as good as the assumptions made about manufacturing cost. They suggested that we provide detailed information on flow of materials so that they could make their own analysis. Readers most interested in costs and conclusions may want to skip this section and pick up at the discussion of operating costs.

A computer program was developed to calculate the volume per hour of all materials flowing through a COM-PLY panel factory. First, the program computes the flow of particleboard through any size particleboard press selected for the factory. This key piece of machinery determines the flow of all other materials through the factory. Then the program computes the amounts of resin binder, catalyst required for rapid cure of resin binder, wax, and cubic feet of wood associated with the hourly flow of particleboard through the press. The program computes particleboard flow for any width and length of press; number of press openings; number of press cycles per hour; waste trimmed from the cured panels; levels of resin, catalyst and wax used; three-layer or homogeneous board; and specific gravity of the board. Table 3 lists values used in the program for Case I and Case II. In Case I, total cycle time for pressing is 6.5 minutes. For a two-stage operation, the particleboard press has a total cycle time of 4.2 minutes and the veneer-applicating press has a total cycle time of 3 minutes.

Table 3.–Amounts assumed for production variables in order to calculate flow of materials through the particleboard section of the COM-PLY panel factory

Variable	Case I	Case II[1]
	. . *Amounts* . . .	
Net width of press (feet)	4	4
Net length of press (feet)	8	24
Press openings	30	14
Press cycles per hour	9.23	14.29
Allowance for width trim (feet)	.33	.33
Allowance for length trim (feet)	.67	.67
Specific gravity of particleboard (percent)	.6	.6
Resin solids in particleboard (percent)	6	6
Wax solids in particleboard (percent)	.5	.5
Average specific gravity of wood supply	.59	.59

[1] Amounts shown are for the particleboard press of a two-stage operation. The hot-press for applying veneers to cores is a 4- by 8-foot by 30-opening low-pressure press and has 20 press cycles per hour.

Green-wood volumes are assumed to be 1.15 times dry-wood volumes–a value reported by Koch (1972). Table 4 lists some computed flow rates for the particleboard portion of COM-PLY panel manufacturing.

The program computes hourly flow of panels produced, veneer-laminating adhesive, veneer, peeling residues, number of peeler logs required, and Btu of fuel required to dry veneer and chips from veneer residue. After the program has calculated the hourly flow of particleboard, it computes the number of particleboard panel cores that can be cut from the particleboard. Next, the hourly dry veneer volume associated with the number of panel cores is computed. Studies (Koenigshof unpublished,[1] McAlister and Taras 1978) have been made for southern pine timber that provide ratios between dry and green veneer volumes, dry veneer and peeler log volumes, and other characteristics. These ratios provide means for correlating log veneer quantities with panel core flow. Ratios used in computations for this study (table 5) are taken from COM-PLY Report 9 (McAlister and Taras 1978). From quantities reported in tables 5 and 6, the reader can compute acres of southern pine timber required to operate a composite panel factory or evaluate other possible combinations of wood residues and veneers that might be used to make panels.

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[1] Data on file U.S. Dep. Agric. For. Serv., For. Sci. Lab., Athens, Ga.

Table 4.–Some of the computed flow of materials for the particleboard operation

Material	Flow					
	Cubic feet per cycle		Cubic feet per hour		Pounds per hour	
	Case I	Case II	Case I	Case II	Case I	Case II
Particleboard pressed	28.2	37.4	259.9	534.1	9,730	19,997
Ovendried wood in particleboard					8,805	18,097
Solid ovendried wood in particleboard			239	492		
Green wood from peeling residue to be chipped					13,303	28,825
Green wood from top logs too small to peel into veneer					5,973	10,512
Resin solids in particleboard					528	1,086
Wax liquid emulsion in particleboard					92	189
Water in particleboard after pressing					352	724

Table 5.–Ratios used for computing the flow of veneer, veneer residues, and linear feet of logs through a COM-PLY panel factory[1]

Ratio	Value
Volume of dry-peeling residue to volume of dry A, B, C, and D veneer yield	0.853
Linear feet of peeler log to cubic foot of dry A, B, C, and D veneer[2]	3.32
Linear feet of small logs from upper part of tree to cubic foot of upper tree stem[2]	3.7
Volume of green peeler log to volume of dry A, B, C, and D veneer	2.22

[1] From McAlister and Taras (1978).

[2] From unpublished studies by G. A. Koenigshof on file at the U.S. Dep. Agric. For. Serv., For. Sci. Lab., Athens, Ga.

One input variable to the program is the moisture content of the green peeler blocks. After the hourly volume of green peeler logs required to operate the factory has been determined, the program computes the amount of water removed during drying of veneer and veneer-peeling residues. Then the program computes the Btu of energy required to remove the water from veneer and veneer-peeling residues. It is assumed that 1,500 Btu are required to remove 1 pound of water from 1/10-inch-thick green veneer, and 1,800 Btu are required to remove 1 pound of water

Table 6.–Average dry volume of veneer and residues per acre in a typical, natural stand of southern pine[1]

Item	Yield per acre	Proportion of total stand volume per acre
	Cubic feet	*Percent*
A & B veneer	121.5	9.0
C veneer	291.1	21.5
D veneer	182.1	13.5
Total full-length veneer	594.7	44.0
Fishtail	43.6	3.2
Total veneer	638.3	47.2
Peeling residue	507.5	37.6
Total block volume	1,145.8	84.8
Top log residue	205.8	15.2
Total-tree volume	1,351.6	100.0

[1] From McAlister and Taras (1978). Based on per-acre values for number of trees, block volume, and tree volume in a typical, natural stand of southern pine.

from green wood chips.

Table 7 lists hourly volume flows for panel cores, veneer, veneer logs, peeling residues, water removed to dry wood, and other quantities that are necessary to select equipment and determine operating costs.

The number of panels laminated each hour depends on the number of panel cores coming from the particleboard press. The number of panel cores produced per hour, therefore, determines the veneer and veneer log requirements, shown in table 7.

The program computes the quantities of adhesive required for laminating veneer to cores. Amount of glue spread on the veneers and particleboard can be varied in the computer program. In our study, the laminating adhesive spread between the core and the veneer was 20 lb/Mft^2 of glueline for a single-stage operation. The adhesive spread between the veneer and the particleboard core was 40 lb/Mft^2 of glueline for a two-stage operation. Table 7 shows hourly amounts of laminating adhesive used for Case I and Case II.

OPERATING COSTS

Operating costs are major determinants of annual net earnings or cash proceeds from the investment. It is emphasized that the operating costs reported here are based on 1975 price levels. In this study, it is assumed that the factory operates 6 days per week and 50 weeks per year. Out of each 24-hour day, it is assumed that there are 22 hours of useful work. Efficiency is thus about 92 percent, or 6,600 hours of production per year. Such high efficiency is possible because only a single item is being made and the setup and startup times are small. Normally, plants that make a variety of particleboards have efficiencies of about 85 percent.

Table 7.—Hourly flows of veneer, veneer logs, panel cores, peeling residues and laminating glue requirements

Material	Amounts per hour	
	Case I	Case II
Panel cores produced (number)	277	600
Dry veneer required for panels including 16 percent waste (square feet)	20,557	44,544
Dry veneer required (cubic feet)	171	371
Green veneer logs required (cubic feet)	380	823
Green logs to be barked (linear feet)	569	1,233
8-foot peeler blocks to be peeled (number)	67	145
Peeling residues produced from cores, roundup and spur trim (cubic feet)	168	364
Green wood required in addition to peeling residues to supply wood particles for particleboard cores (assumed to come from tops of trees above height where peeler blocks occur) (cubic feet)	75	133
Small logs from upper tree stems to be barked for wood particles (linear feet)	279	491
12-foot-long small logs to be barked (number)	32	60
Water removed from green veneer during drying (pounds)	7,254	15,718
Water removed from green wood chips during drying (pounds)	8,966	19,427
Phenol-resorcinol laminating adhesive (resin plus catalyst) for gluing veneer to particleboard core (mixed liquid pounds)	408	1,766

Unit Materials Cost

Wood

Manufacturers of COM-PLY panels would have several potential sources of wood. They could purchase veneer of the grade required for panels and the lowest cost mill residue available for the wood particles in the particleboard. They could purchase tree-length timber, peel veneer of the quality needed from that portion of the tree with a nominal diameter of 8 inches or larger, and convert the peeling residues and portions of the tree too small to peel into wood particles for the particleboard. We have used the second method in this study. Purchasing tree-length timber has distinct advantages which offset its disadvantages.

One advantage of using tree-length timber is that parts of the tree which are too small to peel, as well as the peeling residues from the veneer operation (cores, roundup, spur-trim), can be converted into clean chips of higher quality than mill residues typically used to make particleboard. Practically no waste is generated from such a wood supply. In this study, we assumed that 5 percent waste and scrap would be lost during the particle-chipping operation. Wood residues generated from trimming veneer into 4-foot widths and panel trimming are assumed to be used in the particleboard core. Veneer losses during manufacture are assumed to be 16 percent in computing veneer requirements, but almost all of the lost veneer can be converted into wood particles for the core.

The most important advantage to using full-length trees is that wood particles of optimum size and shape can be made from peeling residues and those parts of the tree too small to peel into veneer. Particles made by chipping roundwood and then milling the chips into flakes are ideal for COM-PLY panels. Much less resin is required to coat large flakes (up to 2 inches long) than to coat particles made from sawmill residues, which typically contain a large percentage of fine material. Although more energy is required to dry flakes and splinters made from green wood than to dry sawmill residues, this higher cost is more than offset by the reduced amounts of waste, scrap wood, and resin.

In 1975, southern pine saw logs cost about $117.25/M board feet (Doyle scale) delivered to the mill (U.S. Dep. Agric. 1977). When converted to cost per green cubic foot, this price is approximately $0.53 for southern pine. Tree-length logs could probably be obtained at less cost per cubic foot because the material in tops is worth less and because harvesting and hauling costs would be somewhat less than for saw logs. COM-PLY panels do not require peeler logs of the quality required to make plywood. Peeler logs as used to make plywood could cost as much as 50 percent more than saw logs. In this study, we assume that green wood for COM-PLY panels would have cost $0.53 per cubic foot in 1975. Since wood shrinks about 15 percent when dried and we assume that 5 percent is wasted in the factory, the cost of dry wood in the panel is about $0.64 per cubic foot when green wood costing $0.53 per cubic foot is used. For the 10-year-investment period in this study, costs of green wood were assumed to increase at a compound rate of 5 percent per year, as tabulated below:

Yearly period	Cost of green wood (dollars/cubic foot)
1	0.530
2	0.557
3	0.584
4	0.614
5	0.644
6	0.676
7	0.710
8	0.746
9	0.783
10	0.822

The volume of veneer in a 1/2-inch-thick COM-PLY panel is about 40 percent of the panel volume, whereas the volume of A, B, C, and D veneer in an average mixture of southern pine trees is over 44 percent of the tree volume (see table 6). Tree-length southern pine timber, therefore, contains just about the right amount of veneer for panel manufacturing. In this process, nearly complete tree utilization is achieved.

High-quality timber is not required for making veneer for COM-PLY panels. Studies on grade and yield for southern pine indicate that COM-PLY panels can be made from veneer in No. 2 saw logs.

Potential manufacturers of COM-PLY panels must consider all the factors discussed and select a low-cost wood supply of their own for analysis of economic feasibility. However, the quality of the COM-PLY panel with regard to durability and dimensional stability is greatly influenced by the type of wood selected to make the flakes for the core. Therefore, performance as well as cost must be considered when determining the type and cost of wood.

Particleboard Phenolic Resin Binder

The source of wood for panels influences the amount of resin required in cores, and resin cost is a major expense. Figure 2 shows industrial average prices for the phenolic resin used in particleboard on a 100 percent solids basis. From 1955 to 1973, the price of phenolic resins steadily declined; then in 1974 the price rose drastically as a result of shortages of petrochemicals. This study is based on the 1975 price of $0.31 per pound for phenolic resin, and we estimated price increase at a compound rate of 5 percent per year.

Particleboard Wax

Liquid wax emulsions are added to particleboard in order to reduce thickness swelling when the particleboard is soaked in water for short periods. These emulsions, roughly half wax solids, were priced at $0.08 per liquid pound in 1975. In this study, we used this 1975 price for wax emulsion and assumed it would increase at a compound rate of 5 percent per year.

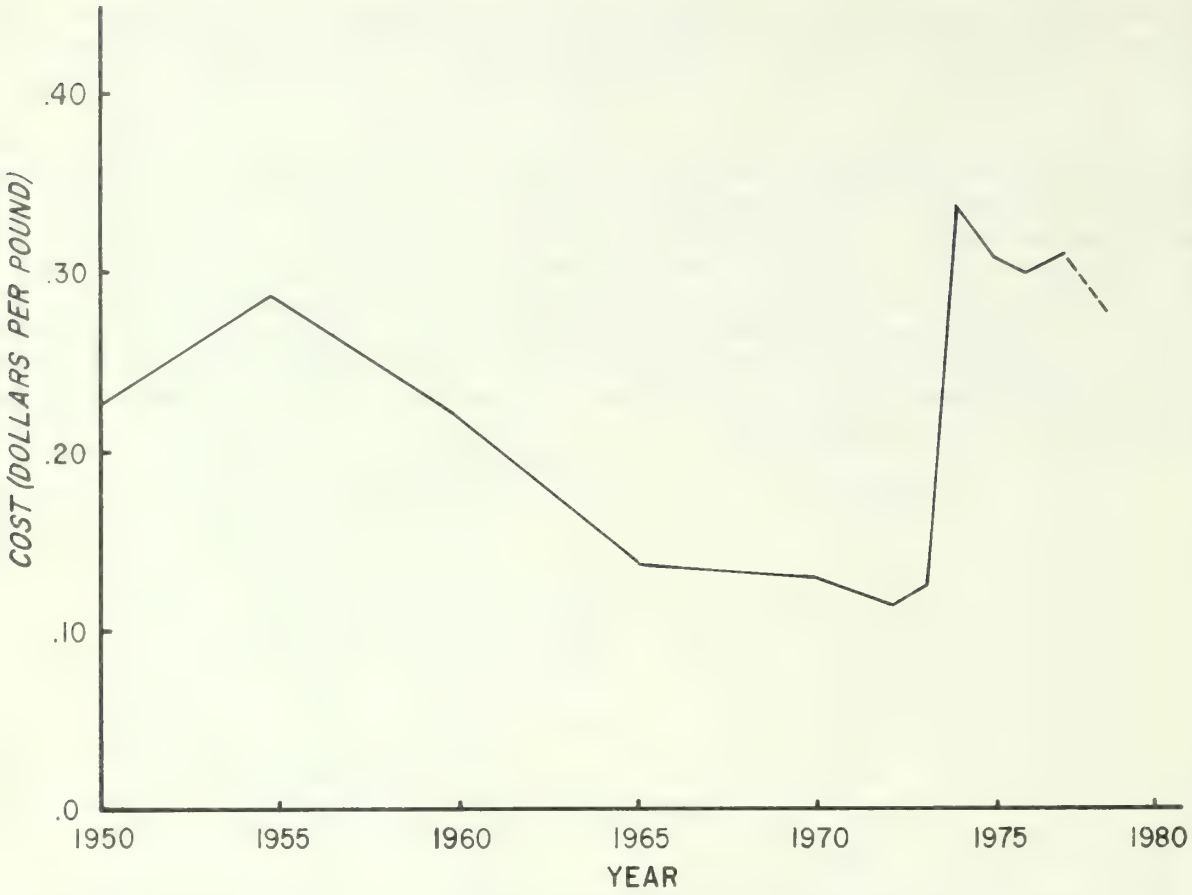

Figure 2.–Price of phenolic resin per dry pound on a 100 percent solids basis.

Laminating Adhesive

Phenolic adhesives are widely used for laminating veneers in plywood. Cost of these adhesives when mixed was about $0.127 per liquid pound in 1975, and we estimated price increase at a compound rate of 5 percent per year.

Total Materials Cost

Total annual cost for materials was estimated by multiplying the quantity of materials flowing per hour times 6,600 hours per year times the unit price of the materials (see table 8).

Labor Cost

Labor costs, which have been rising rapidly since 1961, vary with skills required, fringe benefits, and geographic locations.

Table 9 was developed from industry reviews to show our projected wages in a plant in Arkansas for various levels of skill from 1975 through 1985. We assumed that wages, including fringe benefits, would be at the prevailing rates in that State. Tables 10 and 11 list all of the job descriptions, number of workers, number of shifts worked, wage rates paid, hours worked per day, and daily labor cost for each operation for Case I and Case II. Total daily labor cost was calculated to be $4,407.28 for Case I and $6,680.56 for Case II. This sum multiplied by the 300 days worked per year is the total annual labor cost. At full production capacity, the annual labor cost at the 1975 rate is $1,322,184 for Case I and $2,004,168 for Case II.

The annual cost for labor escalates exponentially from year to year, as indicated by the growth rate in table 9. Of course, the amount of labor required during the beginning years will be less than when the plant reaches full production. In fact, during the first-year construction period (1975), there will be no direct labor cost.

Table 8.–Annual cost of materials for a COM-PLY panel factory for Case I and Case II

Item and Case	Flow of materials per hour		Time worked per year		Unit price		Total annual cost
			Hours		*Dollars*		
Case I							
Wood (green-tree length)	455.0 ft^3	X	6,600	X	0.530	=	1,591,590
Flakeboard resin	528.0 lb (dry)	X	6,600	X	.310	=	1,080,288
Flakeboard wax	91.7 lb (liquid)	X	6,600	X	.080	=	48,418
Laminating adhesive	407.6 lb (liquid)	X	6,600	X	.127	=	341,650
Total							3,061,946
Case II							
Wood (green-tree length)	955.5 ft^3	X	6,600	X	.530	=	3,342,339
Flakeboard resin	1,085.8 lb (dry)	X	6,600	X	.310	=	2,221,547
Flakeboard wax	188.9 lb (liquid)	X	6,600	X	.080	=	99,739
Laminating adhesive	1,766.4 lb (liquid)	X	6,600	X	.127	=	1,480,596
Total							7,144,221

Table 9.–Estimated labor wages (including fringe benefits) for operating a COM-PLY panel factory in Arkansas from 1975 through 1985[1]

Year	Skill level of workers		
	Skilled	Semiskilled	Unskilled
	Dollars per hour		
1975	4.96	4.54	4.02
1976	5.23	4.78	4.24
1977	5.51	5.05	4.47
1978	5.81	5.32	4.71
1979	6.13	5.61	4.97
1980	6.46	5.92	5.24
1981	6.82	6.24	5.52
1982	7.19	6.58	5.82
1983	7.58	6.94	6.14
1984	7.99	7.31	6.47
1985	8.42	7.71	6.83

[1] Wages escalate by the amount $10^{0.023(n-1)}$ where n is 1 to 11 for years 1975 through 1985.

Table 10.- Labor requirements for COM-PLY panel factory (Case I)

Operations or job	Workers	Shifts	Hourly wage rate[1]	Time worked per day	Daily cost for labor
	. . . No	. . . .	Dollars	Hours	Dollars
Log scaler	1	1	4.96	8	39.68
Log-lift driver	2	1	4.54	16	72.64
Barker operator	1	1	4.54	8	36.32
Conveyor chaser	1	1	4.02	8	32.16
Fireman	1	4	4.54	32	145.28
Cutoff sawyer	1	1	4.54	8	36.32
Helper	1	1	4.02	8	32.16
Log sorter	1	1	4.96	8	39.68
Jitney driver (veneer log)	1	1	4.54	8	36.32
Grinding-room man	1	1	4.96	8	39.68
Lathe operator	1	1	4.96	8	39.68
Lathe spotter	1	1	4.54	8	36.32
Clipperman (green)	2	1	4.54	16	72.64
Offbearer	6	1	4.02	48	192.96
Jitney driver (veneer)	1	3	4.54	24	108.96
Dryer tender	1	3	4.54	24	108.96
Dryer feeder	2	3	4.02	48	192.96
Dryer offbearer	4	3	4.02	96	385.92
Glue mixer	1	1	4.54	8	36.32
Veneer plugger	1	3	4.02	24	96.48
Jointer & edge gluer	2	1	4.02	16	64.32
Layup	2	3	4.54	48	217.92
Press operator	2	3	4.54	48	217.92
Jitney driver (warehouse)	2	3	4.54	48	217.92
Panel sawyer	1	1	4.54	8	36.32
Strapper operator	1	1	4.02	8	32.16
Car loader	2	1	4.54	16	72.64
Splitter & slasher	1	1	4.54	8	36.32
Chipper operator	1	1	4.54	8	36.32
Cleanup (screen)	1	1	4.02	8	32.16
Hammermill operator	1	3	4.54	24	108.96
Dryer & screen operator	1	3	4.54	24	108.96
Resin mixer	1	3	4.54	24	108.96
Former operator	1	3	4.96	24	119.04
Trimmer & cooler	1	3	4.54	24	108.96
Millwright	1	3	4.96	24	119.04
Millwright helper	1	3	4.54	24	108.96
Electrician	1	3	4.96	24	119.04
Cleanup	1	3	4.02	24	96.48
Foreman	1	3	6.25	24	150.00
Superintendent	1	1	10.00	8	80.00
Machinist	1	1	4.96	8	39.68
Pipefitter	1	1	4.96	8	39.68
Storeroom man	1	1	4.54	8	36.32
Watchman	1	3	4.02	24	96.48
Shipping clerk	1	1	4.54	8	36.32
Office clerk	1	1	4.54	8	36.32
Sanderman	1	1	4.96	8	39.68
Grader	1	1	4.54	8	36.32
Patcher	2	1	4.54	16	72.64
Total				976	4,407.28

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[1] Hourly rate includes 25 percent for taxes and fringe benefits.

Operations or job	Workers	Shifts	Hourly wage rate[1]	Time worked per day	Daily cost for labor
	. . . *No*		*Dollars*	*Hours*	*Dollars*
Log scaler	1	2	4.96	16	79.36
Log-lift driver	4	2	4.54	64	290.56
Barker operator	1	2	4.54	16	72.64
Conveyor chaser	1	2	4.02	16	64.32
Fireman	1	4	4.54	32	145.28
Cutoff sawyer	1	2	4.54	16	72.64
Helper	1	2	4.02	16	64.32
Log sorter	1	2	4.96	16	79.36
Jitney driver (veneer log)	1	2	4.54	16	72.64
Grinding-room man	1	1	4.96	8	39.68
Lathe operator	1	2	4.96	16	79.36
Lathe spotter	1	2	4.54	16	72.64
Clipperman (green)	2	2	4.54	32	145.28
Offbearer (veneer)	6	2	4.02	96	385.92
Jitney driver (veneer)	1	3	4.54	24	108.96
Dryer tender	1	3	4.54	24	108.96
Dryer feeder	4	3	4.02	96	385.92
Dryer offbearer	8	3	4.02	192	771.84
Glue mixer	1	1	4.54	8	36.32
Veneer plugger	2	3	4.02	48	192.96
Jointer & edge gluer	2	2	4.02	32	128.64
Layup	4	3	4.54	96	435.84
Press operator	2	3	4.54	48	217.92
Jitney driver (warehouse)	2	3	4.54	48	217.92
Panel sawyer	1	2	4.54	16	72.64
Strapper operator	1	2	4.02	16	64.32
Car loader	2	2	4.54	32	145.28
Splitter & slasher	1	2	4.54	16	72.64
Chipper operator	1	2	4.54	16	72.64
Cleanup (screen)	1	2	4.02	16	64.32
Hammermill operator	1	3	4.54	24	108.96
Dryer & screen operator	1	3	4.54	24	108.96
Resin mixer	1	3	4.54	24	108.96
Former operator	1	3	4.96	24	119.04
Trimmer & cooler	1	3	4.54	24	108.96
Millwright	1	3	4.96	24	119.04
Millwright helper	1	3	4.54	24	108.96
Electrician	1	3	4.96	24	119.04
Cleanup	1	3	4.02	24	96.48
Foreman	1	3	6.25	24	150.00
Superintendent	1	1	10.00	8	80.00
Machinist	1	1	4.96	8	39.68
Pipefitter	1	1	4.96	8	39.68
Storeroom man	1	1	4.54	8	36.32
Watchman	1	3	4.02	24	96.48
Shipping clerk	1	1	4.54	8	36.32
Office clerk	1	1	4.54	8	36.32
Sanderman	1	2	4.96	16	79.36
Grader	1	2	4.54	16	72.64
Patcher	2	2	4.54	32	145.28
Press operator	1	3	4.54	24	108.96
Total				1,504	6,680.56

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[1] Hourly rate includes 25 percent for taxes and fringe benefits.

Energy Cost

A COM-PLY panel factory requires two types of energy for its operation–electrical to power motors in machinery and thermal to dry wet wood. Some operations require both electrical and thermal energy, while others require only one. Actual energy costs depend on the volume of materials being processed, efficiency of the machinery fuel type, and fuel costs.

Table 12 lists the major energy-using operations in a COM-PLY panel factory and shows the estimated quantitie of electrical and thermal energy for a given production unit per hour. For example, table 12 shows that drying chip requires 18 kilowatt-hours of electrical energy for every green ton of chips processed and 1,800 Btu of therma energy for every pound of water removed from the chips. The values for energy shown in table 12 are estimates actual values in a factory could vary widely, depending on machine efficiency.

Tables 13 and 14 show the energy computations for Case I and Case II. For example, the amount of green woo to be chipped and dried for Case I (from table 4) is 13,303 pounds per hour of residues and 5,973 pounds per hou of small top logs. The total is 19,276 pounds per hour or 9.6 tons per hour. The estimated electrical energy require for drying chips is 18 kilowatt-hours per green ton (from table 12) times 9.6 green tons per hour, or 172.8 kilowatt hours per hour. For Case I, table 7 shows the amount of water removed from green chips is 8,966 pounds per hou The estimated thermal energy required to dry the green chips is obtained by multiplying 8,966 pounds of water pe hour times 1,800 Btu per pound of water removed or 16,138,800 Btu per hour. The values for electrical energy ar based on full-rated horsepower of motor-driven equipment and must be reduced to 70 percent of the values show in order to be more realistic about actual loads on the motors. For electricity costing \$0.014 per kilowatt-hour, th cost per year for electricity is \$95,592; for thermal energy costing \$0.07 per therm, the cost per year is \$145,649 The total energy cost per year for Case I is \$241,241 in 1975. The annual energy cost for Case II is \$206,306 fo electrical energy and \$325,663 for thermal fuel or a total energy cost of \$531,969 in 1975. In this study, the pric of fuel increases at a compound rate of 5 percent per year.

Other Production Costs

There are various other costs associated with manufacture that need to be accounted for in operating a factory These costs are best obtained from accounting records of an actual factory; the amounts shown in table 15 are roug estimates.

Sales promotion expenses were arbitrarily assumed to be 6 percent of the 1975 sales if the plant had bee operating at full capacity. These expenses were distributed over the first 3 years of operation in declining amounts o 3 percent, 2 percent, and 1 percent.

Depreciation

Depreciation must be computed in order to determine the manufacturing costs, taxable income, and return o investment. We used the straight-line method of depreciation to determine manufacturing cost and the sum-of-the years digit method to determine return on investment.

ANNUAL SALES, OPERATING CASH FLOWS, AND TOTAL MANUFACTURING COST

This section shows the cash proceeds or net earnings that accrue from the manufacturing operation. In computing net earnings, we estimated revenue from sales and then subtracted manufacturing costs and taxes.

Some price has to be assumed for the product. In this analysis, therefore, the prices of COM-PLY panels are assumed to equal those of A–B sanded and C–D unsanded exterior grades of plywood.

It is extremely difficult to accurately predict panel prices because they fluctuate widely with economic conditions. The average f.o.b. mill price of 1/2-inch-thick Standard Exterior southern pine plywood was \$75.50/Mft^2 i 1970 and rose to \$162.67/Mft^2 in 1976 (Evans 1976). Average price for the 6-year period was \$136.36/Mft^2. Thi rise in price equals compound growth rate of about 14 percent for a 6-year period. In 1975, the average f.o.b. mil price for 1/2-inch-thick Standard Exterior southern pine plywood was \$122.00/Mft^2. The year 1975 was a period o recession, low home-building activity, and low plywood prices. We therefore estimated that COM-PLY panel price would increase at a compound growth rate of 5 percent during the investment period from 1975 to 1985. Table 1 shows expected f.o.b. mill prices for COM-PLY 1/2-inch-thick A–B sanded and C–D unsanded exterior-grade COM-PLY panels.

Table 12.–Energy required to make COM-PLY panels

Production operations	Production units per hour	Electrical energy per unit	Thermal energy per unit
		kWh	*Btu*
rking logs	Linear feet of logs	0.004 to 0.012	–
gging waste wood and bark	Green tons	20 to 40	–
nveying chips, logs, etc.	Green tons	35	–
aming peeler blocks	Green tons	–	110,000
g cutoff and slasher saws	Linear feet of logs	0.002	–
g-sorting deck equipment	Linear feet of logs	0.003	–
eling veneer blocks on rotary lathe	Square feet of veneer	0.006	–
neer drying			
. electrical	Square feet of veneer	0.007	–
. thermal	Pounds of water removed	–	1,500
nveying veneer	Square feet of veneer	0.003	–
tching panels	Square feet of panels	0.001	–
ipping round and waste wood into chips	Green tons of wood	17 to 40	
mmermilling chips into particles	Green tons of chips	15 to 25	–
ying chips			
. electrical	Green tons	18	–
. thermal	Pounds of water removed	–	1,800
reening chips	Dry tons of chips	0.3 to 0.5	–
ending particles with resin and resin mixing	Dry tons of particles	8	–
rming particleboard matt	Dry tons of matt	5	–
epress matt	Square feet of matt	0.004	–
ess matt into particleboard			
. electrical	Dry tons of matt	6	–
. thermal			
(1) heat matt	Dry tons of matt	–	120,000 to 160,000
(2) heat cauls (if used)	Dry tons of matt	–	80,000 to 160,000
(3) heat losses			
(a) water evaporation	Dry tons of matt	–	80,000 to 160,000
(b) radiation	Dry tons of matt	–	6,000 to 12,000
(c) convection	Dry tons of matt	–	4,000 to 12,000
nish panels	Square feet of panels	0.004	–
ess panels to apply veneer			
. electrical			
(1) press and prepress panels	Dry tons of panels	6	–
. thermal			
(1) heat panels to cure glue	Dry tons of panels	–	100,000 to 140,000
(2) heat cauls	Dry tons of panels	–	80,000 to 160,000
(3) heat losses			
(a) water evaporation	Dry tons of panels	--	80,000 to 160,000
(b) radiation	Dry tons of panels	–	6,000 to 12,000
(c) convection	Dry tons of panels		4,000 to 12,000

Table 13.–Estimated energy required per hour to produce COM-PLY panels for Case I[1]

Operation	Energy unit		Materials unit		Energy/hour[2]	
					Electrical	Thermal
					kWh	*Btu*
Barking logs	0.006	X	848.0	=	5.09	
Hogging fuel	30.000	X	1.8	=	54.00	
Conveying chips	35.000	X	9.6	=	336.00	
Steaming blocks	110,000.000	X	15.0	=		1,650,000
Log cutoff	.002	X	848.0	=	1.70	
Log sorting	.003	X	848.0	=	2.54	
Peeling veneer	.006	X	20,557.0	=	123.34	
Veneer drying	.007	X	20,557.0	=	143.90	
Veneer drying	1,500.000	X	7,254.0	=		10,881,000
Conveying veneer	.003	X	20,557.0	=	61.67	
Patching panels	.001	X	8,861.0	=	8.86	
Flaking wood	26.000	X	9.6	=	249.60	
Hammermilling	20.000	X	9.6	=	192.00	
Drying chips	18.000	X	9.6	=	172.80	
Drying chips	1,800.000	X	8,966.0	=		16,138,800
Screening chips	.400	X	4.4	=	1.76	
Blending	8.000	X	4.4	=	35.20	
Forming matt	5.000	X	4.9	=	24.50	
Prepress matt	.004	X	32.0	=	.13	
Pressing matt	6.000	X	4.9	=	29.40	
Heating matt	160,000.000	X	8.0	=		1,280,000
Heating cauls	100,000.000	X	8.0	=		800,000
Water loss	80,000.000	X	8.0	=		640,000
Radiation loss	9,000.000	X	8.0	=		72,000
Convection loss	8,000.000	X	8.0	=		64,000
Finish panels	.004	X	8,861.0	=	35.44	
					1,477.93	31,525,000
					X .70[3]	
					1,034.55	

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[1] Factory is assumed to work 6,600 hours per year. Hourly totals for kWh and Btu must be multiplied by this value to obtain yearly totals.

[2] Data may not equal totals due to rounding and truncating.

[3] Electrical energy is 70 percent of total in order to account for motors not running at full-rated horsepower.

Table 14.–Estimated energy required per hour to produce COM-PLY panels for Case II[1]

peration	Energy unit		Materials unit		Energy/hour[2]	
					Electrical	Thermal
					kWh	*Btu*
king logs	0.006	X	1,734.0	=	10.40	
gging fuel	30.000	X	3.8	=	114.00	
nveying chips	35.000	X	19.7	=	689.50	
aming blocks	110,000.000	X	32.6	=		3,585,999
cutoff	.002	X	1,734.0	=	3.47	
sorting	.003	X	1,734.0	=	5.20	
ling veneer	.006	X	44,544.0	=	267.26	
neer drying	.007	X	44,544.0	=	311.81	
neer drying	1,500.000	X	15,718.0	=		23,577,000
nveying veneer	.003	X	44,544.0	=	133.63	
ching panels	.001	X	19,200.0	=	19.20	
pping wood	26.000	X	19.7	=	512.20	
nmermilling	20.000	X	19.7	=	394.00	
ing chips	18.000	X	19.7	=	354.60	
ing chips	1,800.000	X	19,427.0	=		34,968,600
eening chips	.400	X	9.2	=	3.68	
nding	8.000	X	9.2	=	73.60	
ming matt	5.000	X	10.5	=	52.50	
press matt	.004	X	96.0	=	.38	
ssing matt	6.000	X	10.5	=	63.00	
ating matt	140,000.000	X	10.5	=		1,470,000
ating cauls	100,000.000	X	10.5	=		1,050,000
ter loss	80,000.000	X	10.5	=		840,000
diation loss	9,000.000	X	10.5	=		94,500
nvection loss	8,000.000	X	10.5	=		84,000
ish panels	.004	X	19,200.0	=	76.80	
ss veneer	6.000	X	17.4	=	104.40	
at veneer	120,000.000	X	17.4	=		2,087,999
at cauls	120,000.000	X	17.4	=		2,087,999
ter loss	20,000.000	X	17.4	=		347,999
diation loss	9,000.000	X	17.4	=		156,599
nvection loss	8,000.000	X	17.4	=		139,199
					3,189.64	70,489,999
					X .70[3]	
					2,232.75	

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[1] Factory is assumed to work 6,600 hours per year. Hourly totals for kWh and Btu must be multiplied by this value to obtain rly totals.

[2] Data may not equal totals due to rounding and truncating.

[3] Electrical energy is 70 percent of total in order to account for motors not running at full-rated horsepower.

Table 15.–Miscellaneous production costs in operating a COM-PLY panel factory

Cost	Amount		
	Percent of sales	Percent of land, building, and facilities cost	Salary (in 1975)
			Dollars
Production supplies	2.0		
Maintenance supplies	1.0		
Utilities	.1		
General manager			25,000
Office manager			18,000
Office clerks (three at $6,000 each)			18,000
Grade-certification fees	1.0		
Other office administrative expenses	.5		
Facilities maintenance		2.0	
Facilities taxes		.5	
Facilities insurance		.5	
Sales expense	5.0		
Contingency expense	2.0		

Table 16.–Estimated f.o.b. mill prices for 1/2-inch-thick A-B sanded and C-D unsanded exterior-grade COM-PLY panels during the investment period from 1975 to 1985

Year	Price	
	A-B grade	C-D grade
	.... *Dollars per M board feet*	......
1975	231.80	122.00
1976	243.39	128.10
1977	255.56	134.51
1978	268.34	141.23
1979	281.75	148.29
1980	295.84	155.71
1981	310.63	163.49
1982	326.17	171.67
1983	342.47	180.25
1984	359.60	189.26
1985	377.58	198.73

The price of sanded A-B exterior-grade panels was essentially twice that of unsanded C-D exterior-grade panels May of 1976. The price of sanded A-B exterior-grade panels seems to fluctuate between 1.8 and 2.0 times that of sanded C-D exterior-grade panels. This study assumed that the price for sanded A-B panels will be 1.9 times that unsanded C-D panels.

Tables 17 and 18 show the annual cash flows from operating a COM-PLY panel factory over the 10-year period Case I and Case II. In this study, it is assumed that the production level of panels will be zero during the first ir of the investment because of plant construction, 20 percent the second year, 80 percent the third year, and 100 rcent the fourth year. When the factory reaches 100 percent production, it will be operating at an efficiency of 92 rcent.

The cash flows from sales in tables 17 and 18 were computed by multiplying the f.o.b. mill price times the iare footage of panels produced per year. The volume of panels for Case I is 276.9 4- by 8-foot panels per hour, or ,481,280 square feet per year. From table 16, the sales price in 1975 is \$122/Mft^2 for C-D grade panels and 31.80/Mft^2 for A-B grade panels. In table 6 it is shown that the quantity of veneer available from southern pine nds is approximately 20 percent A and B grades and 80 percent C and D grades. Therefore, the mix of panel grades ed in this study is assumed to be 20 percent A-B panels and 80 percent C-D panels. All are assumed to contain terior resin binder in the particleboard and in the veneer-to-particleboard glueline. The yearly quantity of A-B terior-grade panels produced is 11,696 M square feet; that of C-D exterior panels is 46,785 M square feet. To strate method used, sales for the first 4 years are computed in table 19 only for Case I.

Buildings, facilities, and machinery have some terminal salvage value at the end of the 10-year-investment period. cause terminal salvage is revenue from a sale and is taxable, it is treated as a sales item during the last year of the estment period.

Computing the cash flows for operating costs in tables 17 and 18 is similar to computing the cash flows for sales. e inflation rate used was 5 percent except for wage rates, which escalated at the rate shown in table 9. The general nager, office manager, and clerks were assumed to be hired on a full-time basis at the beginning of the second year. es promotion occurred only during the first 3 years, declining from \$252,600 the first year to \$84,200 in the rd year. Only 50 percent of the expense for facilities was assumed to occur the first year, but the entire expense curred in subsequent years and escalated at a rate of 5 percent.

Total operating costs for tax computations were found by totaling the costs for raw materials, production, adnistration, sales promotion, facilities, contingencies, sales, and depreciation. For example, the operating cost for se I in the fourth year, when full production is reached, is shown as \$8,091,700. Depreciation is included with the erating cost because the Internal Revenue Service allows depreciation to be deducted as an expense for tax comtations. Depreciation began in the second year, when most of the investment for machinery and facilities had been de.

The taxable income is the difference between sales and total operating cost, including depreciation. For the irth year, the taxable income is \$1,654,300. For this study, we assumed a Federal tax rate of 48 percent and adional state and local tax charges of 4 percent for a total tax rate of 52 percent. Tax on income for the fourth ir is \$860,200 and after-tax profit is \$794,100.

To obtain the net annual earnings for the fourth year, the depreciation (which was subtracted as a production st for computing taxes) is added back to the after-tax profit. The net earnings for the fourth year are \$2,199,200.

Notice that a negative income tax is shown for the first and second years. The Federal Government does not ke tax refunds to companies that have a loss from operating. However, a large company could charge off these ses against other parts of the business that were operating profitably; therefore, they have been left in this analysis. r a company that could not write off the losses that occur during the first 2 years, there would be zero income and negative net earnings for both years.

Operating costs shown in tables 17 and 18 can be used to compute the 1975 manufacturing cost of a panel. This st is computed by discounting the amount for each item during the fourth year back to the 1975 cost. For most ms, the 1975 price is obtained by multiplying 0.8638 times the 1978 value to account for a 5 percent annual comund increase in prices. However, change in labor costs is somewhat higher, and its multiplier is 0.8531 times the 78 cost. Total expense for sales promotion was averaged for the 10 years to give an average yearly cost for 1975. aight-line depreciation for a 10-year period was used for computing depreciation cost for 1975. After making se adjustments, the 1975 values were divided by 58,481,280 square feet of panels produced per year to obtain cost per thousand square feet. Table 20 shows the 1975 estimated manufacturing cost for COM-PLY panels de in Arkansas for Case I and Case II.

Computing the operating cost shown in tables 17 and 18 is difficult, and accurate data are not easily obtained.

Table 17. Ten-year cash flow from operations of a COM-PLY panel factory (Case I)[1]

Item	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
						Thousands of dollars				
A. Sales										
Panels (A–B exterior)	0	569.4	2,391.3	3,138.5	3,295.5	3,460.2	3,633.3	3,814.9	4,005.7	4,205.9
Panels (C–D exterior)	0	1,198.6	5,034.3	6,607.5	6,937.8	7,284.7	7,649.0	8,031.4	8,433.0	8,854.6
Terminal salvage	0	0	0	0	0	0	0	0	0	175.6
Total	0	1,768.0	7,425.5	9,746.0	10,233.3	10,745.0	11,282.2	11,846.3	12,438.6	13,236.2
B. Raw materials										
Logs	0	334.2	1,403.8	1,842.5	1,934.6	2,031.3	2,132.9	2,239.5	2,351.5	2,469.1
Particleboard resin	0	226.9	952.8	1,250.6	1,313.1	1,378.8	1,447.7	1,520.1	1,596.1	1,675.9
Particleboard catalyst	0	0	0	0	0	0	0	0	0	0
Particleboard wax	0	10.2	42.7	56.0	58.9	61.8	64.9	68.1	71.5	75.1
Laminating adhesive	0	71.7	301.3	395.5	415.3	436.0	457.8	480.7	504.8	530.0
Total	0	643.0	2,700.6	3,544.6	3,721.8	3,907.9	4,103.3	4,308.5	4,523.9	4,750.1
C. Production expense										
Direct labor	0	697.0	1,469.9	1,549.9	1,634.1	1,723.0	1,816.7	1,915.5	2,019.7	2,129.6
Power and fuel	0	50.7	212.8	279.3	293.2	307.9	323.3	339.5	356.4	374.2
Production supplies	0	35.4	148.5	194.9	204.7	214.9	225.6	236.9	248.8	261.2
Maintenance supplies	0	17.7	74.3	97.5	102.3	107.4	112.8	118.5	124.4	130.6
Utilities	0	1.8	7.4	9.7	10.2	10.7	11.3	11.8	12.4	13.1
Total	0	802.5	1,912.9	2,131.3	2,244.6	2,364.0	2,489.8	2,622.2	2,761.7	2,908.7
D. Administrative expenses										
General manager	0	26.2	27.6	28.9	30.4	31.9	33.5	35.2	36.9	38.8
Office manager	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Clerks (3)	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Grade-certification fees	0	17.7	74.3	97.5	102.3	107.4	112.8	118.5	124.4	130.6
Other	0	8.8	37.1	48.7	51.2	53.7	56.4	59.2	62.2	65.3
Total	0	90.6	178.6	216.8	227.6	239.0	251.0	263.5	276.7	290.5
E. Sales promotion	252.6	168.4	84.2	0	0	0	0	0	0	0
F. Facility expenses										
Maintenance	32.2	67.5	70.9	74.5	78.2	82.1	86.2	90.5	95.0	99.8
Taxes	8.0	16.9	17.7	18.6	19.5	20.5	21.6	22.6	23.8	25.0
Insurance	8.0	16.9	17.7	18.6	19.5	20.5	21.6	22.6	23.8	25.0
Total	48.2	101.3	106.4	111.7	117.3	123.2	129.3	135.8	142.6	149.7
G. Contingency expenses	0	35.4	148.5	194.9	204.7	214.9	225.6	236.9	248.8	261.2
H. Sales expense	0	88.4	371.3	487.3	511.7	537.2	564.1	592.3	621.9	653.0
I. Cost of operations (B+C+D+E+F+G+H+L)	300.8	3,685.9	7,083.3	8,091.7	8,257.2	8,440.1	8,641.3	8,861.8	9,102.5	9,364.5
J. Taxable income (A–I)	-300.8	-1,918.0	342.3	1,654.3	1,976.1	2,304.9	2,640.9	2,984.5	3,336.1	3,871.7
K. Income tax (52% X J)	-156.4	-997.3	178.0	860.2	1,027.6	1,198.5	1,373.3	1,552.0	1,734.8	2,013.3
L. Depreciation										
Machinery	0	1,229.6	1,106.7	983.7	860.8	737.8	614.8	491.9	368.9	245.9
Facilities	0	526.7	474.1	421.4	368.7	316.0	263.4	210.7	158.0	105.3
Total	0	1,756.4	1,580.8	1,405.1	1,229.5	1,053.8	878.2	702.6	526.9	351.3
M. After-tax profit (J–K)	-144.4	-920.6	164.3	794.1	948.5	1,106.3	1,267.6	1,432.6	1,601.3	1,858.4
N. Net earnings (M+L)	-144.4	835.8	1,745.0	2,199.2	2,178.0	2,160.2	2,145.8	2,135.1	2,128.3	2,209.7

Item	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
	Thousands of dollars									
A. Sales										
Panels (A-B exterior)	0	1,233.7	5,181.5	6,800.7	7,140.8	7,497.8	7,872.7	8,266.3	8,679.7	9,113.6
Panels (C-D exterior)	0	2,597.3	10,908.5	14,317.4	15,033.2	15,784.9	16,574.1	17,402.8	18,273.0	19,186.6
Terminal salvage	0	0	0	0	0	0	0	0	0	215.0
Total	0	3,830.9	16,090.0	21,118.1	22,174.0	23,282.7	24,446.8	25,669.2	26,952.6	28,515.3
B. Raw materials										
Logs	0	701.9	2,947.9	3,869.2	4,062.6	4,265.8	4,479.1	4,703.0	4,938.2	5,185.1
Particleboard resin	0	466.5	1,959.4	2,571.7	2,700.3	2,835.3	2,977.1	3,125.9	3,282.2	3,446.3
Particleboard wax	0	20.9	88.0	115.5	121.2	127.3	133.7	140.3	147.4	154.7
Laminating adhesive	0	310.9	1,305.9	1.714.0	1,799.7	1.889.7	1,984.1	2,083.3	2,187.5	2,296.9
Total	0	1,500.3	6,301.2	8,270.3	8,683.8	9,118.0	9,573.9	10,052.6	10,555.3	11,083.0
C. Production expense										
Direct labor	0	1,056.6	2,228.1	2,349.3	2,477.0	2,611.8	2,753.8	2,903.6	3,061.5	3,228.0
Power and fuel	0	111.7	469.2	615.8	646.6	678.9	712.9	748.5	786.0	825.3
Production supplies	0	76.6	321.8	422.4	443.5	465.7	488.9	513.4	539.1	566.0
Maintenance supplies	0	38.3	160.9	211.2	221.7	232.8	244.5	256.7	269.5	283.0
Utilities	0	3.8	16.1	21.1	22.2	23.3	24.4	25.7	27.0	28.3
Total	0	1,287.1	3,196.1	3,619.8	3,811.1	4,012.5	4,224.6	4,447.9	4,683.0	4,930.6
D. Administrative expenses										
General manager	0	26.2	27.6	28.9	30.4	31.9	33.5	35.2	36.9	38.8
Office manager	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Clerks (3)	0	18.9	19.8	20.8	21.9	23.0	24.1	25.3	26.6	27.9
Grade-certification fees	0	38.3	160.9	211.2	221.7	232.8	244.5	256.7	269.5	283.0
Other	0	19.2	80.4	105.6	110.9	116.4	122.2	128.3	134.8	141.5
Total	0	121.5	308.6	387.4	406.8	427.1	448.4	470.9	494.4	519.1
E. Sales promotion	547.3	364.9	182.4	0	0	0	0	0	0	0
F. Facility expenses										
Maintenance	35.9	75.4	79.2	83.2	87.3	91.7	96.3	101.1	106.1	111.4
Taxes	9.0	18.9	19.8	20.8	21.8	22.9	24.1	25.3	26.5	27.9
Insurance	9.0	18.9	19.8	20.8	21.8	22.9	24.1	25.3	26.5	27.9
Total	53.9	113.1	118.8	124.7	131.0	137.5	144.4	151.6	159.2	167.2
G. Contingency	0	76.6	321.8	422.4	443.5	465.7	488.9	513.4	539.1	566.0
H. Sales expense	0	191.5	804.5	1,055.9	1,108.7	1,164.1	1,222.3	1,283.5	1,347.6	1,415.0
I. Cost of operations (B+C+D+E+F+G+H+L)	601.2	5,805.3	13,168.6	15,600.7	16,090.0	16,615.1	17,177.7	17,779.9	18,423.6	19,111.0
J. Taxable income (A-I)	-601.2	-1,974.3	2,921.3	5,517.4	6,084.0	6,667.6	7,269.1	7,889.3	8,529.0	9,404.3
K. Income tax (52% X J)	-312.6	-1,026.6	1,519.1	2,869.1	3,163.7	3,467.2	3,779.9	4,102.4	4,435.1	4,890.3
L. Depreciation										
Machinery	0	1,555.3	1,399.8	1,244.2	1,088.7	933.2	777.6	622.1	466.6	311.1
Facilities	0	595.0	535.5	476.0	416.5	357.0	297.5	238.0	178.5	119.0
Total	0	2,150.3	1,935.2	1,720.2	1,505.2	1,290.2	1,075.1	860.1	645.1	430.1
M. After-tax profit (J-K)	-288.6	-947.7	1,402.2	2,648.4	2,920.3	3,200.5	3,489.2	3,786.8	4,093.9	4,514.1
N. Net earnings (M+L)	-288.6	1,202.6	3,337.5	4,368.6	4,425.5	4,490.6	4,564.3	4,646.9	4,739.0	4,944.1

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[1] Data may not add to totals due to rounding and truncating.

Table 19.–Sales for first 4 years for Case I

Year	Item	Annual production at 6,600 hours per year		Price f.o.b. mill		Level of production		Sales
				Dollars per M				*Thousand dollars*
1975	A-B panels	11,696,256	X	231.80	X	0	=	0
	C-D panels	46,785,024	X	122.00	X	0	=	0
Total sales								0
1976	A-B panels	11,696,260	X	243.39	X	0.2	=	569,350
	C-D panels	46,785,024	X	128.10	X	.2	=	1,198,632
Total sales								1,767,982
1977	A-B panels	11,696,256	X	255.56	X	.8	=	2,391,276
	C-D panels	46,785,024	X	134.51	X	.8	=	5,034,443
Total sales								7,425,719
1978	A-B panels	11,696,256	X	268.34	X	1.0	=	3,138,573
	C-D panels	46,785,024	X	141.23	X	1.0	=	6,607,449
Total sales								9,746,022

Table 20.–Estimated manufacturing cost in 1975 for COM-PLY panels made in Arkansas for Case I and Case II

Item	Case I		Case II	
	Annual cost adjusted to 1975 prices	Manufacturing cost	Annual cost adjusted to 1975 prices	Manufacturing cost
	Dollars	*Dollars per M board feet*	*Dollars*	*Dollars per M board feet*
Logs	1,591,590	27.22	3,342,339	26.38
Particleboard resin	1,080,288	18.47	2,221,547	17.53
Wax	48,418	.83	99,739	.79
Veneer adhesive	341,650	5.84	1,480,596	11.68
Direct labor	1,322,184	22.61	2,004,168	15.82
Power and fuel	241,241	4.13	531,969	4.20
Other production expenses	260,987	4.46	565,521	4.46
Administrative expenses	187,284	3.20	334,639	2.64
Sales promotion	50,514	.86	109,456	.86
Facilities expense	96,498	1.65	107,754	.85
Contingency	168,379	2.88	364,852	2.88
Sales expense	420,948	7.20	912,131	7.20
Depreciation	966,100	16.52	1,182,640	9.33
Total	6,776,081	115.87	13,257,351	104.62

otential manufacturers of COM-PLY panels probably have a good source of data in their own company records. By using their own data and making computations similar to those shown in this section, manufacturers can accurately estimate the factory cost for their own company.

CASH FLOWS AND INTERNAL RATE OF RETURN

Potential manufacturers of COM-PLY panels want to know what return on their investment they can expect on the cash proceeds or net earnings. The return on investment is found by determining interest rates on the basis of the present-value concept. In simple terms, if we invest $100 today at 6 percent interest, the value 1 year from today is $106. The $106 is called the future sum. The future sum includes the original amount (present value) plus interest accumulated (return on investment). The $100 is analogous to investments or cash outlays to build a factory, while the $106 is analogous to cash proceeds resulting from profitable operation.

The process of computing the present value of future sums at a given interest rate is referred to as discounting. In this study, the annual cash outlays (such as payout for investments) are considered as negative future sums and annual cash proceeds (such as net earnings from profitable operation) are considered as positive future sums. The object of the analysis is to find the compound interest or discount rate at which the present value of the cash outlays equals the present value of the cash proceeds. This procedure is widely used for evaluating the economic feasibility of investments and is often referred to as a discounted cash flow analysis. The appropriate compound interest or discount rate is found by trial and error.

A low interest rate is selected and the net annual cash flows (outlays and proceeds) or future sums are converted to their present value on the basis of the rate selected. If the cumulated net annual cash flow is positive then the present value of the cash proceeds is greater than the present value of the cash outlays for the 10 years of operation. In that case, a higher interest rate is selected and the procedure is repeated until a rate is found at which the positive present value of cash proceeds equals the negative present value of cash outlays. This interest or discount rate is called the internal rate of return.

Internal rates of return were computed for Case I and Case II by the procedure outlined. The rate for Case I was a somewhat disappointing 10.18 percent. Most manufacturing firms could probably find a less risky investment that would earn 10 percent or more. For Case II, on the other hand, the calculated rate of return is 21.56 percent, which is quite attractive.

In this era of high inflation, many manufacturing firms find that the price of investment capital is somewhere near 15 percent. That is somewhere near the amount they must pay to borrow for a new venture. Tables 21 and 22 show the cash flows for Cases I and II at a discount rate of 15 percent.

The first column in tables 21 and 22 shows the year or period of investment. Year 0 represents the beginning of year 1, but the other numbers 1 through 10 represent yearend times. The next column shows cash outlays for investment and is taken from table 2 for Case I. The values are negative because they represent cash outlays except for the value at year 10. This value represents working capital (cash, inventory, accounts receivable) that is recovered at the end of the investment period. The recovered working capital is treated as a positive nontaxable cash flow.

Column 3 is taken from the net earnings (table 17). If production operations are unprofitable, the net earnings will be negative. However, if the production operation is profitable, the net earnings are positive and represent cash proceeds.

Column 4 is the sum of columns 2 and 3 and represents net annual cash flows.

Column 5 lists the present-value factor for a 15 percent interest rate. At rates of return less than 15 percent, a company might be better off to invest elsewhere. The values in column 4 represent future sums at the end of the year indicated. By multiplying the values in column 4 by the present-value factor in column 5, the amount in column 4 is discounted (moved backward through time) to its present value (shown in column 6). For example, at the end of year 5, the net annual cash flow for Case I was $2,178,000 and the present value of annual return was $1,082,900. In other words, if we had invested $1,082,900 at time zero at a compound interest rate of 15 percent, we would have a future sum of $2,178,000 at the end of 5 years.

Column 7 shows the cumulative present values of annual cash flows in column 6. At a discount rate of 15 percent, the $11,983,600 investment in Case I would not be paid back in 10 years. The internal rate of return is 10.18 percent. In other words, if we had used present-value factors for a discount rate of 10.18 percent, the investment would have been paid back at the end of the 10th year.

The discounted cash flow analysis for Case II is shown in table 22. For Case II, at a discount rate of 15 percent, the $15,952,900 investment would be paid back in 8 years. The internal rate of return for Case II is 21.56 percent.

Table 21. Cash flows at a 15 percent discount rate for a COM-PLY panel factory during a 10-year-investment period for Case I[1] [2]

Year	Outlay (investment)		Proceeds (net earnings)		Net annual cash flow[3]		Present value[3]			
							At 15%		Annual return	Cumulative
					Thousands of dollars					
0	-390.1	+	0	=	-390.1	X	1.0000	=	-390.1	-390.1
1	-4,292.6	+	-144.4	=	-4,437.0	X	.8696	=	-3,858.2	-4,248.4
2	-6,646.6	+	835.8	=	-5,810.8	X	.7561	=	-4,393.8	-8,642.2
3	-654.3	+	1,745.0	=	1,090.7	X	.6575	=	717.2	-7,925.0
4	0	+	2,199.2	=	2,199.2	X	.5718	=	1,257.4	-6,667.6
5	0	+	2,178.0	=	2,178.0	X	.4972	=	1,082.9	-5,584.7
6	0	+	2,160.2	=	2,160.2	X	.4323	=	933.9	-4,650.8
7	0	+	2,145.8	=	2,145.8	X	.3759	=	806.7	-3,844.1
8	0	+	2,135.1	=	2,135.1	X	.3269	=	698.0	-3,146.2
9	0	+	2,128.3	=	2,128.3	X	.2843	=	605.0	-2,541.2
10	1,433.3	+	2,209.7	=	3,643.0	X	.2472	=	900.5	-1,640.7

[1] The investment is not repaid at a discount rate of 15 percent interest in 10 years.
[2] Internal rate of return for 10-year-investment period is 10.18 percent.
[3] Data may not equal totals due to rounding and truncating.

Table 22. Cash flows at a 15 percent discount rate for a COM-PLY panel factory during a 10-year-investment period for Case II[1] [2]

Year	Outlay (investment)		Proceeds (net earnings)		Net annual cash flow[3]		Present value[3]			
							At 15%		Annual return	Cumulative
					Thousands of dollars					
0	-379.2	+	0	=	-379.2	X	1.0000	=	-379.2	-379.2
1	-5,634.1	+	-288.6	=	-5,922.6	X	.8696	=	-5,150.1	-5,529.3
2	-8,685.2	+	1,202.6	=	-7,482.6	X	.7561	=	-5,658.0	-11,187.2
3	-1,254.4	+	3,337.5	=	2,083.0	X	.6575	=	1,369.6	-9,817.6
4	0	+	4,368.6	=	4,368.6	X	.5718	=	2,497.7	-7,319.9
5	0	+	4,425.5	=	4,425.5	X	.4972	=	2,200.3	-5,119.6
6	0	+	4,490.6	=	4,490.6	X	.4323	=	1,941.4	-3,178.2
7	0	+	4,564.3	=	4,564.3	X	.3759	=	1,715.9	-1,462.3
8	0	+	4,646.9	=	4,646.9	X	.3269	=	1,519.1	56.8
9	0	+	4,739.0	=	4,739.0	X	.2843	=	1,347.1	1,403.9
10	3,047.3	+	4,944.1	=	7,991.5	X	.2472	=	1,975.4	3,379.3

[1] The payback period is 7.96 years at a 15 percent discount rate.
[2] Internal rate of return for 10-year-investment period is 21.56 percent.
[3] Data may not equal totals due to rounding and truncating.

I requires an investment of about $12 million to produce 58,481,280 square feet of panels per year. Case II
ires an investment of about $16 million and produces 126,720,000 square feet of panels per year. In other
ds, a 33 percent increase in investment over that required for Case I will more than double productive capacity
g the Case II two-stage method.

DISCUSSION AND CONCLUSIONS

This study shows that a two-stage system for assembling composite panels yields a much higher rate of return
a one-stage system for assembling composite panels. For the two-stage system, using 1975 prices for panels and
, the return on investment was 21.56 percent. An after-tax return on investment of 20 percent or greater is con-
red favorable by most manufacturers. Furthermore, this rate may be conservative. Prices for panels in 1975 were
ut 12 percent below the average price for panels for the years 1972 through 1976. It seems clear that manu-
ure of COM-PLY panels is economically feasible.

Firms that are already manufacturing particleboard and veneer might realize returns greater than 20 percent
manufacturing COM-PLY panels. The conversion investment would be less than the initial investments shown
, and positive annual cash flows would occur sooner than if a new plant were built. This approach would make
e for other reasons. So many particleboard plants have been built in recent years that there is too much pro-
tive capacity in the United States. As a result, many particleboard plants in the United States are yielding a very
internal rate of return. The earning capacity of such plants could be improved by converting them to COM-PLY
el production.

It should also be pointed out that Case II, which appears quite profitable, represents a single, arbitrarily selected
bination of machinery. Some other combination might prove even more profitable. For example, a standard 40-
ning plywood press might be used to apply veneer facings instead of a 30-opening press, as used in Case II. A
dard 4- by 24-foot by 20-opening particleboard press would have to be used in tandem with the 40-opening ply-
d panel press. It appears, however, that these machines would increase volume of production by one-third for a
modest increase in investment.

Consumer demand for particleboard often peaks a year or two after the peak demand for plywood, primarily
use demand for plywood is greatest during a housing boom. After a housing boom subsides, the need for ply-
d drops off, as it did late in 1973. Subsequently, construction of shopping centers and manufacture of furniture
ease, creating a strong demand for particleboard. Therefore, a manufacturer can weather market fluctuations by
ducing both COM-PLY panels and particleboard in one factory. He can shift production to the product in great-
demand.

Potential manufacturers should carefully compare the manufacturing costs for COM-PLY panels (table 20) with
se for manufacturing plywood. One of the greatest expenses in making conventional plywood is the cost of wood.
ing periods of peak demand for plywood, the prices for stumpage increase. COM-PLY panels can more completely
ze the tree, easing supply pressure during periods of peak demand. If the supply of logs within a reasonable dis-
e from a plywood mill is insufficient, the mill can be forced to close. A plywood plant faced with a limited tim-
supply could convert to composite panels and continue to operate on the limited supply of logs for many years.
version is possible because fewer logs of lower quality are needed for COM-PLY panels. A manufacturer of COM-
panels has a distinct raw-materials cost advantage. Wood represents a smaller proportion of the cost of a COM-
panel than a plywood panel. For COM-PLY panels, the cost for resin binder, wax, and laminating adhesive is
ter than for wood. These nonwood costs are more stable and changes in them normally do not coincide with
nges in wood costs.

The sizes of logs available for making plywood sheathing seem certain to decline. This study shows that it is
nomically feasible to manufacture COM-PLY panels now. A handsome return is indicated for the investment
od from 1975 to 1985. As time passes, the advantage of COM-PLY panels over conventional plywood is likely
crease.

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Investment, production costs, and profitability estimates for manufacture of COM-PLY panels in the South are presented. It is possible to obtain a 20 percent or greater after-tax internal rate of return on an investment in manufacturing COM-PLY panels. The study shows that a manufacturing system that assembles the panels in two stages is more economical than a system that assembles the panels in a single stage.

Keywords: Manufacturing costs, [illegible], [illegible] panel manufacture, composite panels, plywood costs.

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A COMPREHENSIVE BIBLIOGRAPHY ON VACATION HOMES AND RECREATIONAL LANDS IN THE UNITED STATES

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March 1980
Southeastern Forest Experiment Station
Asheville,North Carolina

A COMPREHENSIVE BIBLIOGRAPHY ON VACATION HOMES AND RECREATIONAL LANDS IN THE UNITED STATES

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INTRODUCTION

Overview of the Markets

This bibliography lists all the known literature relating to vacation homes and recreational lands. Vacation homes and recreational lands are sometimes difficult to define, but they share two characteristics: they are privately owned and they are utilized only for seasonal recreational purposes. The category of vacation homes includes resort condominiums; hunting cabins; homes for vacation now and retirement later; summer cottages; etc. The category of recreational land includes scattered vacation-home sites; raw-land-investment subdivisions; vacation-home subdivisions with a few improvements; complete, high-amenity recreational communities, etc.

Few other land or housing submarkets have received as much national attention as did the markets for vacation homes and recreational lands during the period from 1969 to 1975. The first part of this 6-year period was characterized by an incredible expansion in supply and demand for the two interrelated commodities. The latter part of this period was characterized by an equally incredible decline in demand, with enormous numbers of consumer problems, environmental degradation, financial losses, and associated negative publicity. Since 1975, demand has again increased, although the types, quality, and sophistication of the products offered have changed considerably.

The following text should be useful in directing reader use of the bibliography. It describes the evolution of the vacation-home and recreational-land markets and the current supply and demand factors.

Evolution of the Markets

Historically, two basic types of recreational-land development have occurred in this country. The first was a scattering of individual lots in secluded areas. Favorite locations were near lakes, in the mountains, and on the seashores. Typically, lots were purchased from farmers or ranchers, and many were on marginally productive or non-productive land. Lots usually were small and density was frequently high, with very few public facilities, if any. Most houses constructed on these lots were small and were not intended as permanent living quarters, e.g., a hunting cabin in the Maine woods, a lake cottage in the Adirondacks, or a Swiss villa in the Smoky Mountains. Large mansions built by very wealthy people also represent a type of scattered development, but these did not and do not occur in sufficient numbers to justify close attention.

Scattered-lot development is still occurring, but the market has shifted mainly to more organized land development and sales promotion.

The second type of development was a series of platted lots in scenically attractive areas. Again, lots were small (usually at urban densities), and public facilities and services were mini-

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[1] This bibiliography is part of a larger study of vacation homes in the United States and was sponsored by the Southeastern Forest Experiment Station, Clemson, South Carolina, and the Resources Program and Assessment Office, U.S. Forest Service, Washington, D. C.

mal. For the most part, developments were located close to metropolitan areas in an attempt to capture the mass markets. Many of these developed areas have evolved into communities of primary residences. Typical examples are found on Cape Cod, the Jersey Shore, and St. Petersburg, Florida.

During the 1920's, mass marketing of new recreational land began in Florida, and, to a lesser degree, in California. A similar phenomenon began in the late 1950's and early 1960's, spreading throughout the United States and continuing into the early 1970's.

Developers could sell land by mail. All that was required was to tie up the land through purchase of options and make minimal improvements, hire a sales force, launch an advertising campaign, and start the selling. Many developers got rich on the down payments alone.

At first, developers sold retirement lots; later they switched from a retirement to an investment sales pitch. At this point, the real abuses began. By 1970, the land-merchandising business had become a gigantic industry.

Probably no single group harmed the land-development industry or created as negative an image in the public's eye as did the raw-land merchandisers. The proportion of lots built upon was extremely low, land was prematurely subdivided, amenities or services provided were few, promises were frequently broken, and most buyers became dissatisfied.

The leisure home "subdivision" began to occur in the mid-1960's. Land within a certain distance of metropolitan areas was marketed mainly to users in that area. Often, some recreational amenities such as man-made lakes, swimming pools, and golf courses were developed. The general philosophy of developers was to construct the beginnings of a real community by making site improvements, constructing housing, and providing some developed recreational amenities. However, the business is still one of merchandising land. Every major metropolitan area in the United States has at least a few second-home communities nearby. This market is essentially people who actuallly intend to use the property for leisure-time pursuits, as opposed to those interested merely in speculative land investment.

The vacation-home subdivision probably has the greatest range of quality and amenities of any of the recreational-property concepts. A large number of both good and poor projects exist throughout the country.

A development frequently referred to as a recreational "community" began to occur in the late 1960's. Here, although developers were still making most of their money from land sales, their time-frame was greatly extended and their plans included extensive development, often including the construction of housing. The market today is predominantly a user market of home buyers rather than speculative lot buyers. Land planning in these communities is the most sophisticated in the industry. Most of these developments include well-developed recreational facilities such as golf courses, marinas, and ski slopes. Front-end investments in recreational amenities and site improvements are high, and the companies either building or financing such projects generally are large corporate enterprises.

The market focuses on families with high incomes who usually can afford to fly considerable distances to their project. Speculative investment still occurs, but often it includes housing in addition to land. These projects exhibit the greatest likelihood of financial success in establishing a lasting and viable community of real worth.

Community-type projects, although limited to only the affluent consumer, provide almost all the necessary public services and facilities, in addition to a wide variety of recreational amenities. Many of these communities are being advertised as "new towns." Usually, they are fairly high in quality, but they frequently do not have the complete infrastructure associated with a well-developed urban environment.

Several other types of recreational properties, in addition to the developments mentioned previously, are also available. One is the resort condominium, which became popular in the late 1960's. Compared with total acres devoted to recreational-land vacation-home projects, the magnitude of condominium projects is relatively small. However, in many parts of the country (e.g., Lake Tahoe, the Florida coast, the Caribbean, and Hawaii), they have become extremely popular. For the most part, condominiums are located within the vacation-home communities along with single-family, detached vacation homes and individually owned recreational lots.

Another concept is the "club." One type of club has the land remaining under a single ownership, such as the developer or a club association. Legal platting and almost all other actions required by public law are thus eliminated. Club members do not receive a deed; instead, they are assigned "exclusive use rights" to a specific site.

Still another club concept involves developers who own several campgrounds. A consumer purchases a membership in the club, then either by reservation or on the basis of first come first served is entitled to use the sites at any of the developer's campgrounds.

Other opportunities in recreational land are also becoming available to the consumer as shared ownership or undivided interest. As with campgrounds, it now is possible to buy a portion of a recreational unit rather than the entire unit. With shared ownership, the property purchased is measured not only in units of space but also in units of time. Thus, the consumer can pay one-quarter of the total selling price of a condominium unit and be entitled to its use for one-quarter of the year, either for a continuous 3-month period or for 13 weeks distributed throughout the year. Because the entry fee is considerably smaller than for the other types of recreational properties, this approach opens the market to many more persons.

Traditionally, the recreational-land-development industry has been fragmented and characterized by a wide variety of participants ranging from the unscrupulous rip-off artist to the legitimate "community" developer. Respectability of the industry has been questioned severely by the public, the media, and political decisionmakers. In many instances, such questioning has been thoroughly justified; in many others, unfair generalizations have been extended to all recreational-land developers.

Thus, the market for privately owned seasonal recreational property has undergone considerable change. Many innovations have been introduced, and significant peaks of high and low demand have been realized.

Magnitude of Current Markets

Reliable figures for the total number of recreational properties, especially the lots, are not available. Fragmented data from several sources, however, can be used to provide some approximate base figures. A review of recreational-land projects registered with the U.S. Office of Interstate Land Sales Registration (OILSR) shows that over 5 million lots were registered from 1968 to 1978 in 4,400 projects, of which about 4.4 million acres are subdivided land. An estimated two-thirds of all recreational-land communities in the country have registered with OILSR. If the non-registered projects are included, the totals are probably closer to 6,000 projects involving 7.5 million lots and 6 million acres.

A national opinion survey, undertaken in 1973 by the Opinion Research Corporation of Princeton, New Jersey, revealed that 8.5 percent of all households owned a recreational lot. This percentage represented some 5.4 million lots. To estimate accurately the total number of both sold and unsold recreational lots is impossible. However, some surveys indicate that 12 to 15 million recreational lots currently exist in this country. Even this is probably a conservative estimate.

For vacation homes, the most reliable figures on existing stock are available from the U.S. Bureau of the Census. Frequent estimates have been made by many participants in the housing industry, but they represent only fragmented, educated guesses. Unfortunately, not even the Census has provided a well-defined count of vacation homes.

In 1970, nearly 3 million households owned vacation homes. Assuming an approximate annual increase of 100,000 new homes during the past few years, the total standing stock of vacation homes in the United States is perhaps 3.75 million for 1978. This would mean that slightly over 5 percent of all households owns a vacation home, and that this type of unit accounts for slightly less than 5 percent of the total housing stock.

Finally, some estimates can be made for the extent of use of vacation homes. The number of days that owners usually occcupy their unit averages between 50 and 80. Visits tend to be frequent, but the average length of stay per visit tends to be only a few days. The average family size of owners is 3.1 persons, indicating approximately 650 million person-day visits to vacation homes for members of families owning the units. At least 10 percent of the units are also occupied by renters, bringing the total number of person-days annually spent in vacation homes in the United States to perhaps 750 million.

At first glance the market for privately owned recreational properties appears insignificant. The importance of these properties becomes more apparent when considering the number of persons annually in a state of flux between primary and vacation residences, the resultant impacts upon the host community, and the many new types of products being offered the consumer. Entries in this bibliography touch all of these issues and many others.

Organization

The bibliography contains 619 entries and is divided into 5 major sections and 17 subsections.

Part I concerns the evolution of the markets for vacation homes and recreational land, including the three major periods: the formative years (pre-1969); the peak years (1969 to 1972); and the recent years of change (1973 to present). Also included are entries intended to expose some of the numerous problems associated with the recreational-land-development industry during its periods of peak and decline—consumer rip-off, environmental degradation, and premature development.

Part II lists entries that analyze the market for vacation homes and recreational lots, as well as elements of supply and demand. Although most entries concern local or regional studies, several national surveys are included. A subsection on location of recreational properties is included also.

Part III concerns the consumer. Included are subsections on consumer characteristics, consumer guides, and consumer financing. It should be noted that materials on consumer characteristics are also included in many of the national and regional studies listed in Part II.

Part IV lists entries which describe impacts of vacation homes and recreational-land developments upon their host community. Specific subsections deal with environmental and economic impacts.

Part V includes a variety of entries devoted to guidelines for recreational-land developers, resort condominiums, the time-share concept, and newsletters and directories.

Although the bibliography is believed to be the most complete ever compiled on the subject, two areas are omitted: (1) building designs for vacation homes; and (2) problems and legal suits of individual land companies in recent years. Numerous articles have been written about both areas, but most have been restricted to nonanalytical design brochures or newspaper reports.

PART I.
EVOLUTION OF THE MARKETS

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Ragatz, Richard L., and H. Ken Cordell
1980. A comprehensive bibliography on vacation homes and recreational lands in the United States. U.S. Dep. Agric. For. Serv., Res. Pap. SE-202, 31 p. Southeast. For. Exp. Stn., Asheville, N. C.

This bibliography contains 619 references on vacation homes and recreational lands. It is divided into five major parts: I—evolution of the markets, II—analyzing the markets, III—the consumer, IV—impacts from recreational properties, and V—miscellaneous.

Keywords: Markets, land development, condominiums, recreational properties.

Ragatz, Richard L., and H. Ken Cordell
1980. A comprehensive bibliography on vacation homes and recreational lands in the United States. U.S. Dep. Agric. For. Serv., Res. Pap. SE-202, 31 p. Southeast. For. Exp. Stn., Asheville, N. C.

This bibliography contains 619 references on vacation homes and recreational lands. It is divided into five major parts: I—evolution of the markets, II—analyzing the markets, III—the consumer, IV—impacts from recreational properties, and V—miscellaneous.

Keywords: Markets, land development, condominiums, recreational properties.

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PROSPECTIVE INGROWTH OF SOUTHERN HARDWOODS BEYOND 1980

by

Stephen G. Boyce and Herbert A. Knight

United States
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May 1980
Southeastern Forest Experiment Station
Asheville, North Carolina

PROSPECTIVE INGROWTH OF SOUTHERN HARDWOODS BEYOND 1980

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ABSTRACT.—In contrast with a prospective decrease in the ingrowth of southern pine, prospective ingrowth for southern hardwoods is equal to or greater after 1980 than before. Investments in cultural practices to favor pines have not been as effective as the biological, social, and economic forces that favor hardwoods, especially on nonindustrial private forest lands. A rational response to these trends is to increase the use of hardwoods for marketable products.

Keywords: Southern hardwoods, ingrowth, natural regeneration.

1. SUMMARY

1.1 The Findings

Prospective ingrowth for hardwoods in 12 Southern States is increasing. The increase is indicated to be equal to or greater after 1980 than before.

Investments in cultural practices to favor pines have not been as effective as the biological, social, and economic forces that favor hardwoods.

The majority of nonindustrial private forest (NIPF) owners, by pursuing their best interest in social and economic situations, passively permit the biologically better adapted hardwoods to naturally increase after the harvest of pines.

The interaction of biological, social, and economic forces explains why the prospective ingrowth for southern timber after 1980 is decreasing for pines and increasing for hardwoods.

1.2 Implications of the Findings

A rational response to reduced availability of pine and increased availability of hardwood timber is to invent more ways to use all kinds of hardwoods for marketable products.

The maintenance of timber production on a majority of NIPF lands, about 60 to 70 percent of the South's commercial forest land, apparently depends on the use of timber harvesting to enhance the values desired by the owner. These values may not include timber as the primary benefit. The harvest of timber must be scheduled and the age and area classes of stands arranged to return more benefits to the landowners than just the value of the stumpage.

1.3 Important Items of Evidence

The number of 2- and 4-inch hardwoods increased in 12 Southern States inventoried since 1956 (fig. 2, sec. 3.1). A net decline occurred in Arkansas because of conversion of forest lands to other uses.

The ingrowth of hardwoods has been increasing for 3 to 4 decades as evidenced by increases in the number of trees in diameter classes from 6 to 20 inches in all 12 States (figs. 1–23, sec. 3).

Increases in the number of eastern redcedar, an inflammable tree, are good indicators of improved fire protection over the past 20 to 30 years. Improved fire protection has also contributed to increased numbers of hardwood trees (sec. 4.2).

Before 1945, the area in hardwood forests was limited by shifting agriculture—the clearing of hardwood forests for row crops, farming these lands for a decade or less, then retiring the lands and permitting them to naturally succeed to pines

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(sec. 4.2).

Between 1945 and 1965, dislocations in agriculture, increased industrialization of the South, and change in attitudes toward land ownership contributed to rapid cropland retirement. The majority of NIPF owners, pursuing their own interest in these changing social and economic situations, passively permitted retired agricultural lands to naturally develop as pine stands. Both the proportion of pine volume and the total area of commercial forest land increased (sec. 4.2, table 3).

On a majority of NIPF lands, natural hardwood stands are passively permitted to develop after harvest of pine stands. Since 1965, less than half of the harvested pine stands were regenerated to pine. Thus, pursuit of personal interests by most NIPF owners now results in an increase in hardwoods (sec. 4.2).

The evidence is that a majority of NIPF owners have never perceived long-term forestry investments to be in their interest (sec. 4). The relative proportions of pine and hardwood timber in the South have resulted from the passive attitudes of these landowners, who control 60 to 70 percent of the commercial forest land.

2. INTRODUCTION

2.1 Purpose for This Paper

In the Southern United States, why is ingrowth of pines, which are the objects of most cultural investments, likely to decrease while that of hardwoods, which receive little cultural encouragement, is increasing?

This Paper was written to answer this question.

2.2 Overview of the Paper

The answer is found in the social and economic forces that affect the activities of all landowners, regardless of their reasons for owning forest lands or their desires for management. Social and economic forces influence landowner perceptions of forestry investments. Most of the pine and hardwood timber now harvested and most of the growing stock recorded for the South regenerated and grew as an incidental result of social and economic changes, operating along with natural, biological forces.

On forest-industry lands, public lands, and some NIPF ownerships, cultural investments are perceived to be an advantage. However, we find evidence that the majority of NIPF landowners passively permit the growth of timber; these landowners sell pine timber but do not make investments to maintain pines. In the absence of such investments, biological forces favor hardwoods over pines.

We examine (sec. 4) the interaction of biological, social, and economic forces prior to 1945 when perceptions of landowners were different from after 1945. The year 1945 is important as an obvious turning point for both economic forces and social attitudes affecting land management in the South.

But first, it is important to document the decline in pines and increase in hardwoods. A greatly reduced rate of ingrowth for southern pines after 1980 was identified and documented in an earlier paper (Boyce and Knight 1979a). The prospective increase for hardwood ingrowth after 1980 is documented here. We use stand charts (sec. 3) to indicate prospective increases in hardwood ingrowth in 12 Southern States. A minimum description of the charts is required, because the change in numbers of trees between successive inventories is self-evident.

Then, we examine the implications of these findings (sec. 5) for those dependent on southern timber.

3. EVIDENCE FOR INCREASES IN HARDWOOD INGROWTH

3.1 Increased Rates of Hardwood Regeneration

Future ingrowth of hardwood timber is determined by the number of 2- and 4-inch trees that can grow through the 5-inch-diameter window and become growing stock. For hardwoods, the rate of movement of trees through this window is ultimately determined by the rate of natural regeneration. Artificial regeneration of hardwoods represents such a small area that this origin for hardwoods can be ignored.

Although many variables are involved, the single-most-important indicator of future ingrowth is the number of 2- and 4-inch trees. Diameter distributions (fig. 1) for successive inventories clearly indicate changes in rates of regeneration, ingrowth of trees that add to the growing-stock volumes, and changes in the number of trees in the large-diameter classes. For example, an increase in the number of 2- and 4-inch trees signals increases in prospective ingrowth. And, the rates of harvest for hardwoods larger than 12

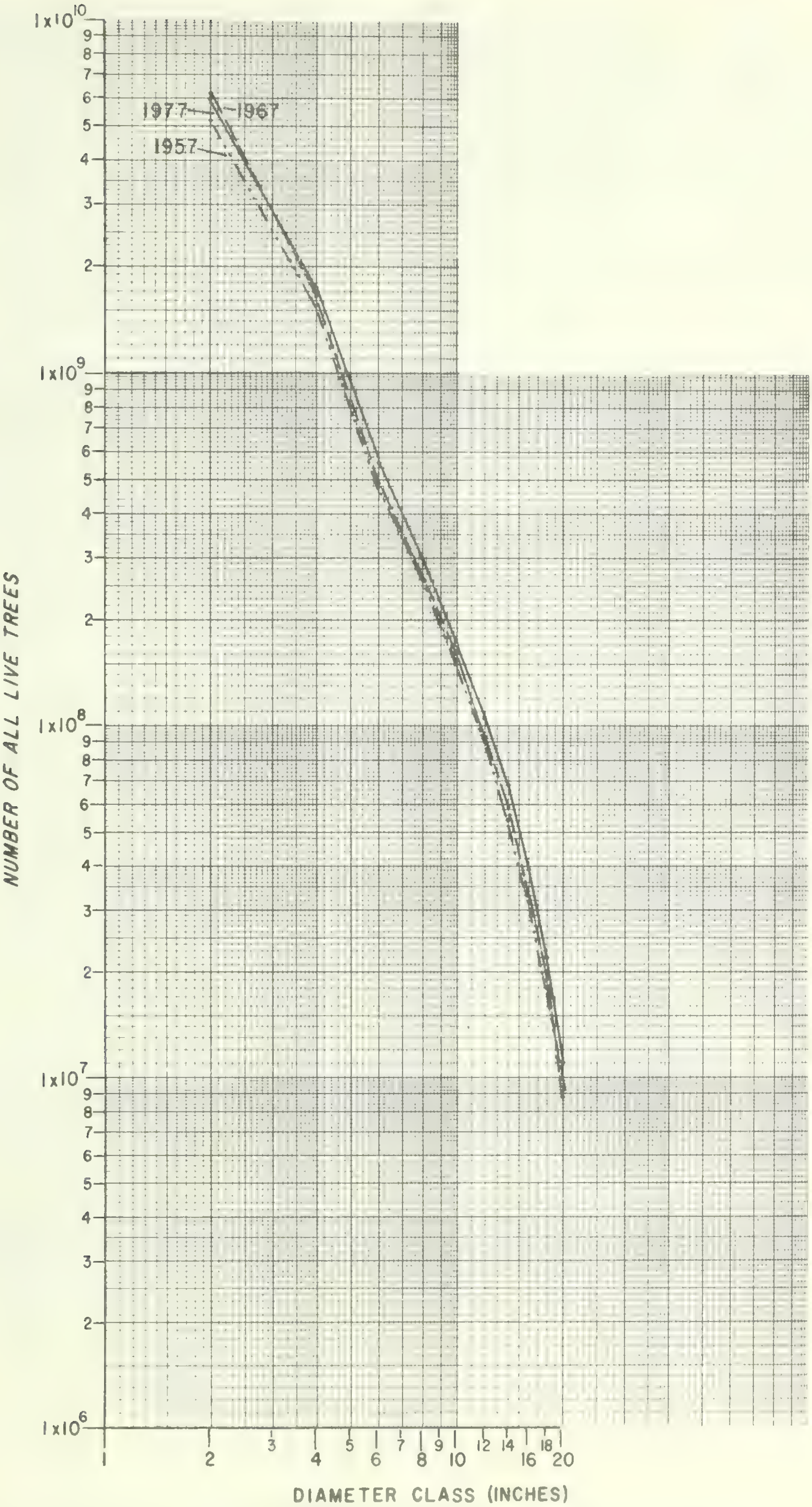

Figure 1.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in Mississippi, 1957, 1967, 1977.

inches d.b.h. is indicated by the steep slope of the curve for trees larger than 12 inches. The decrease in relative numbers of trees larger than 12 inches can be examined by aligning a straightedge with the points for the 2- to 12-inch trees (fig. 1). The deviation of the curve from the straightedge for trees larger than 12 inches suggests the rates of harvest and other forms of mortality for these larger trees.

Stand tables can be projected into the future if certain assumptions are made about rates of regeneration, rates of mortality, the movement of trees from smaller to larger diameter classes, and the harvest of trees from the larger diameter classes (Larson and Goforth 1970). However, changes in the shapes of two successive stand curves and changes in the rates of regeneration are difficult to project from inventory data. Ingrowth can be projected for the near future, such as 1 to 2 decades, once the number of 2- and 4-inch trees is known. The rates of mortality for the future can be assumed to be the same as for the historic part.

In Mississippi, the rates of mortality for 2- and 4-inch trees changed very little for about 20 years. This lack of change is indicated by the almost parallel lines on the stand charts for the 2- and 4-inch trees (fig. 1). For these small-diameter trees, the most important change is in the relative numbers of trees. The change in numbers is important because it reflects varying rates of regeneration.

Variations in rates of regeneration by States can be compared by plotting the percentage of change in number of trees for the dates of inventory (fig. 2). In Mississippi, between 1957 and 1967 the number of 2- and 4-inch hardwoods increased by 1.1 million, or 18 percent (fig. 1). In 1977 the increase was only 2 percent, and the number of trees increased by about 144,000.

Although smaller than in the preceding decade, the 2 percent increase occurred while large areas of hardwood forests in the Delta were being cleared (Murphy 1978). Increases in hardwood regeneration outside the Delta were greater than were the losses from forest clearings. The chart (fig. 1) reveals an increase in the number of hardwoods in all diameter classes by 1977. However, the relatively large number of 2- and 4-inch trees indicates potential ingrowth of hardwoods beyond 1980 equal to or somewhat greater than for the past decade.

An important observation is the increase in the number of 2- and 4-inch hardwoods since 1956 for all the Southern States inventories except Arkansas (fig. 2). In Arkansas the number of 2- and 4-inch trees declined about 1.5 percent between 1959 and 1969. During this period, there was a net decline in the amount of forest land (Van Sickle 1970). Most of the decline occurred in bottomland hardwoods, where about 2 million acres of forest were converted to production of agricultural crops. This conversion resulted in a 7 percent reduction in growing-stock volume for

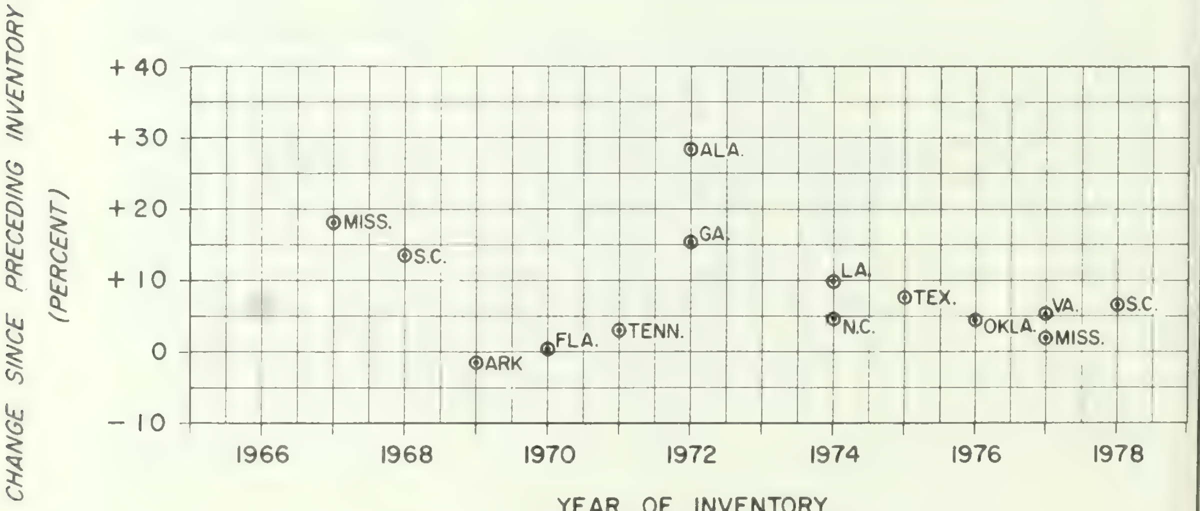

Figure 2.—Percentage change in the number of 2- and 4-inch hardwoods for States, by date of inventory. For example, in 1967 there was 18 percent more 2- and 4-inch hardwoods in Mississippi than in the 1957 inventory.

hardwoods. However, the relatively large numbers of 2- and 4-inch hardwoods (fig. 3) indicate that the prospective ingrowth after 1980 is at least as large as in the past decade. The realization of this potential ingrowth depends to a large extent on future rates of conversion of forests to other uses.

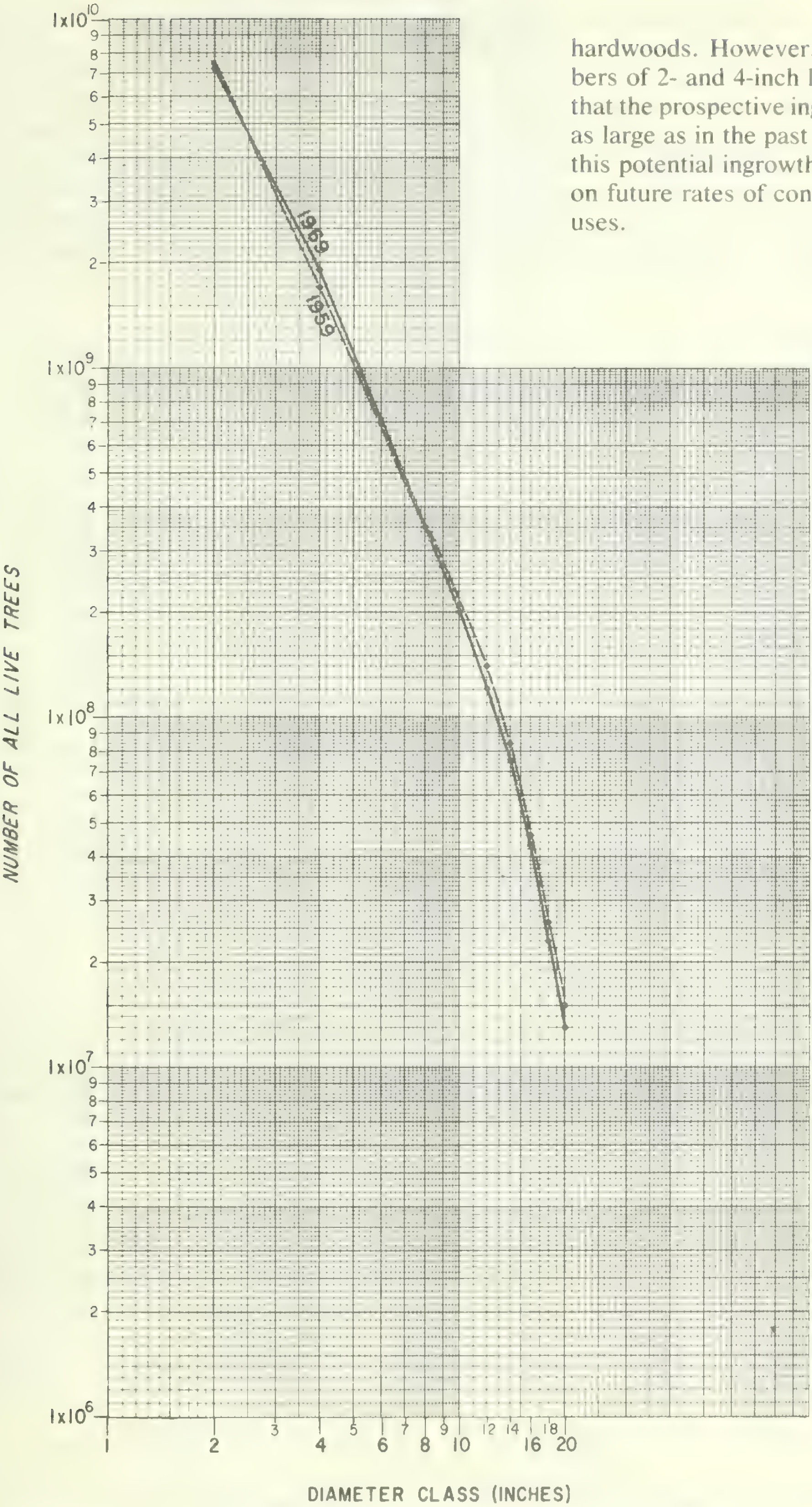

Figure 3.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in Arkansas, 1959, 1969.

Prospective ingrowth for hardwoods in the South has been increasing for 3 to 4 decades. This increase is evident when we examine the percentage of change in numbers of 6-, 8-, 10-inch and larger trees for inventories made since 1957 (figs. 4, 5). The number of hardwoods increased in all of these diameter classes for all States except Arkansas and Louisiana. The relatively small decline in these two States is related to the clearing of forests for agriculture (Van Sickle 1970; Murphy 1975).

Between 1964 and 1974 the forest area in Louisiana declined about 9 percent (Murphy 1975). During this period the growing-stock volume of hardwoods decreased. Fewer trees were found in 1974 than in 1964 in the 6-inch class and in the 10-inch and larger diameter classes (fig. 6). However, the number of 2-inch hardwood trees

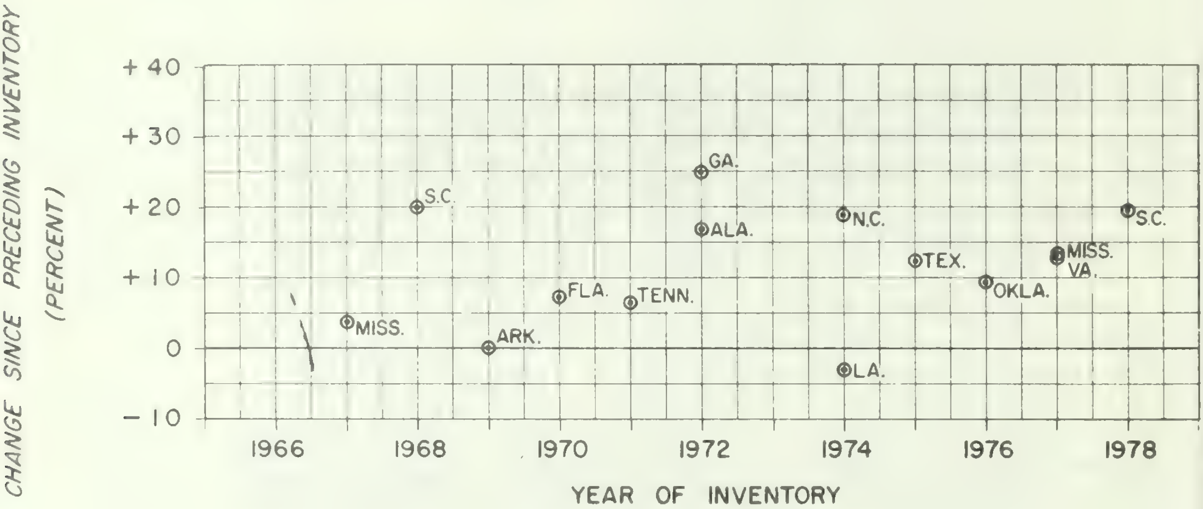

Figure 4.—Percentage change in the number of 6- and 8-inch hardwoods for States, by date of inventory. For example, in 1967 there was 4 percent more 6- and 8-inch hardwoods in Mississippi than in the 1957 inventory.

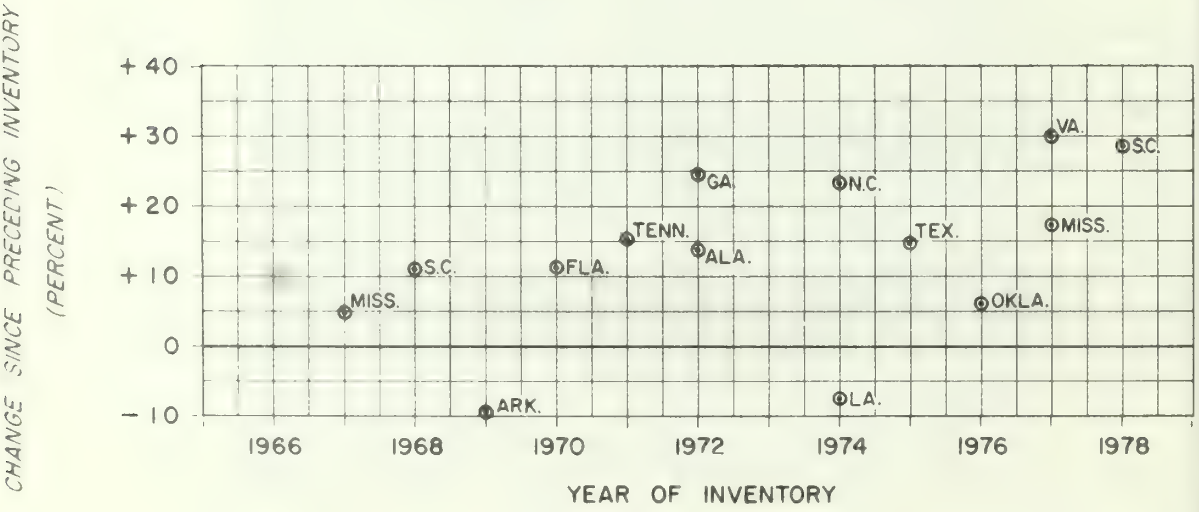

Figure 5.—Percentage change in the number of 10-inch and larger hardwoods for States, by date of inventory. For example, in 1967 there was 5 percent more 10-inch and larger hardwoods in Mississippi than in the 1957 inventory.

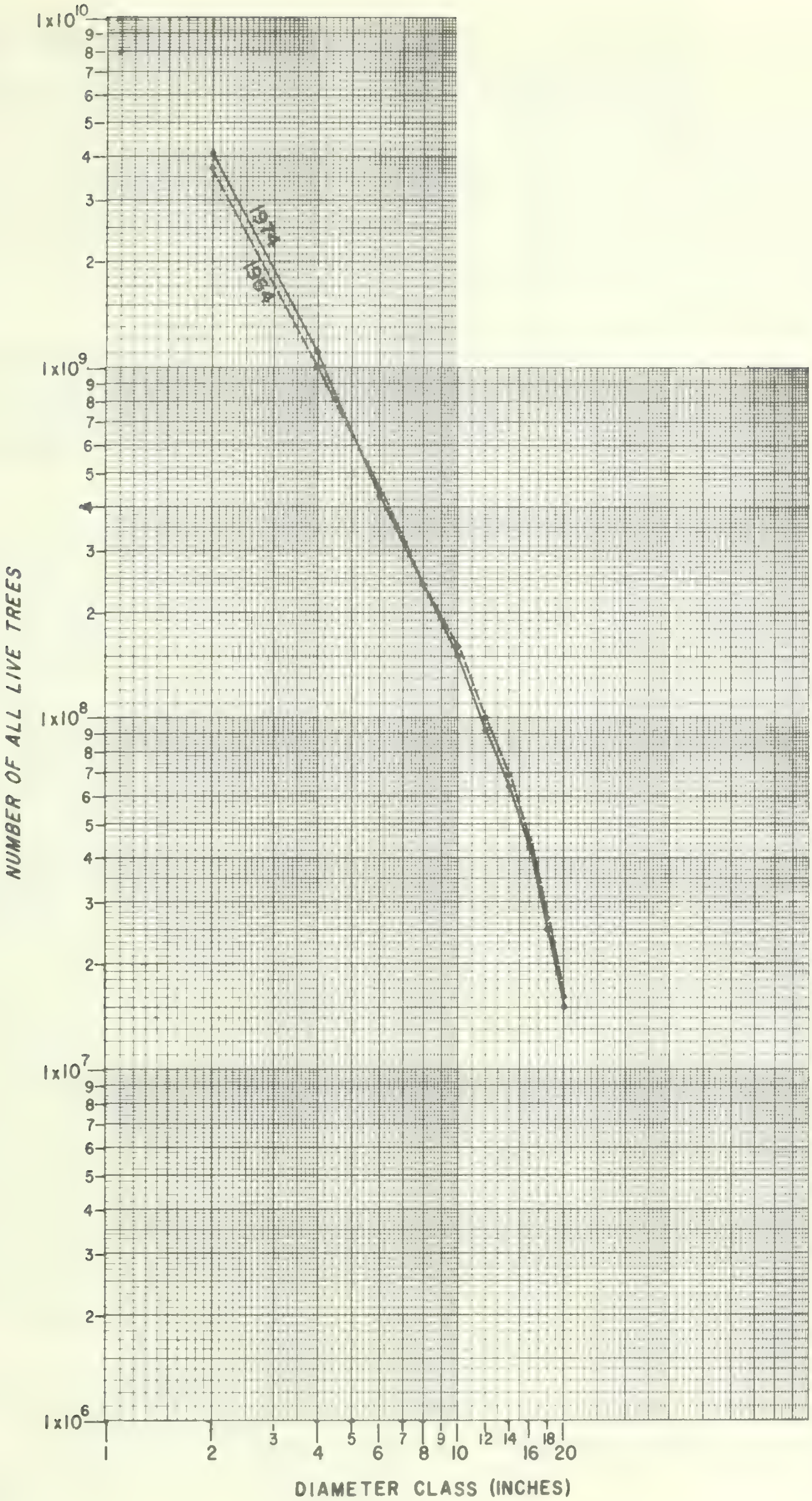

Figure 6.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in Louisiana, 1964, 1974.

increased. The loss of hardwood forests in the Delta is the principal reason for a small decline in hardwood growing stock. For the State as a whole, there is a prospective increase in ingrowth of hardwoods after 1980 (fig. 6).

The important evidence is the increased rates of hardwood regeneration. Increases are found in Mississippi, Arkansas, and Louisiana, where the largest areas of forest have been cleared for agriculture (Frey and Dill 1971; Krause 1970). Increases in the numbers of 2- and 4-inch hardwoods increase the prospective ingrowth after 1980.

3.2 Prospective Ingrowth, by Ownership Class, in Mississippi

Nonindustrial private forest (NIPF) owners hold most of the hardwood trees in Mississippi (figs. 7, 8, 9). This ownership class not only has most of the 2- and 4-inch trees but also the majority of hardwoods larger than 10 inches in diameter.

In the 1977 inventory, a smaller number of 2-inch hardwoods were found on NIPF lands than in 1967. However, there was an increase in the number of trees in all larger diameters. The relatively large number of 2- and 4-inch trees indicates prospective ingrowth equal to, if not somewhat greater than, that in the past decade (fig. 7).

On forest industry and public lands, the number of hardwoods increased for all diameter classes between 1967 and 1977 (figs. 8, 9). The increases in 2- and 4-inch trees for both of these ownership classes indicate increased prospective ingrowth after 1980.

Data comparable to that from Mississippi are available to examine prospective ingrowth, by ownership classes, only for the Southern States of Virginia, North Carolina, South Carolina, Georgia, and Florida. Data from these States indicate increased prospective ingrowth for hardwoods for all ownership classes.

3.3 Prospective Ingrowth by Physiographic Province in South Carolina

The number of hardwood trees increased in all diameters in South Carolina between 1958 and 1978 (fig. 10). Prospective ingrowth after 1980 increased.

Different species of hardwoods occur in the Piedmont physiographic province than occur in the Coastal Plain. However, there appear to be no important differences in prospective ingrowth between these provinces (figs. 11, 12, 13). The Northern Coastal Plain has more hardwoods in all diameter classes than either the Southern Coastal Plain or the Piedmont province.

An examination of the inventory data for Mississippi, Georgia, and Virginia provided no evidence for important differences between the Coastal Plain and the Piedmont for prospective ingrowth of hardwoods.

3.4 Prospective Hardwood Ingrowth Documented for Florida, Tennessee, Georgia, Alabama, North Carolina, Texas, Oklahoma, and Virginia

The total number of hardwood trees increased in these eight States between the most recent inventories (figs. 14, 15, 16, 17, 18, 19, 20, 21). The relatively large increase in the number of trees larger than 4 inches d.b.h. indicates that rates of hardwood regeneration in these States have been increasing for 4 to 5 decades. If the current trend of passively permitting hardwoods to occupy lands from which pine is harvested (Boyce and Knight 1979a) continues, the number of 2- and 4-inch hardwoods can be expected to continue to increase for another decade or longer. However, declines in the total land area for commercial forests can eventually reduce the rates of hardwood regeneration and the potential ingrowth.

The difficulty in predicting net results is illustrated by trends in Oklahoma. The northwestern counties in Oklahoma are dominated by the oak-hickory forest type, which has been declining in area for the past 20 years. The forest area decreased about 4 percent between 1956 and 1966, and decreased another 12 percent between 1966 and 1976 (Sternitzke and Van Sickle 1968; Murphy 1977). In spite of this loss in area of hardwood forest, there is a continued slow increase in the number of 2- and 4-inch hardwood trees (fig. 20). Prospective ingrowth after 1980 is greater than in 1966.

Also, in Tennessee between 1961 and 1971, about 600,000 acres of commercial forest land, mostly hardwood forests, went to other uses (Murphy 1972). However, the number of trees increased in all diameter classes (fig. 15). The relatively large number of 2- and 4-inch hardwood trees indicates prospective ingrowth after 1980 equal to that before 1971.

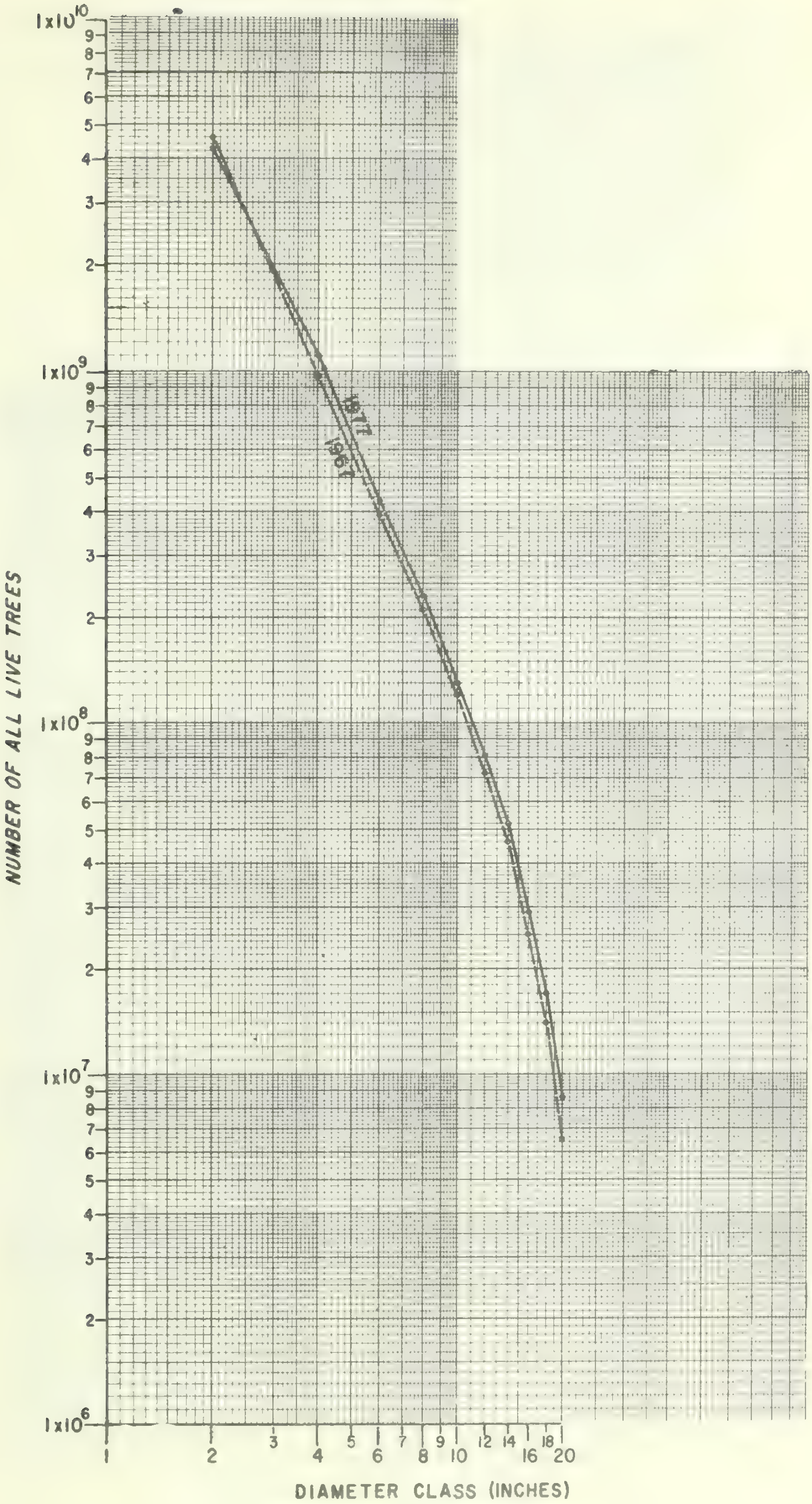

Figure 7.—Distribution of all live hardwood trees on the nonindustrial private class of ownership in Mississippi, 1967, 1977.

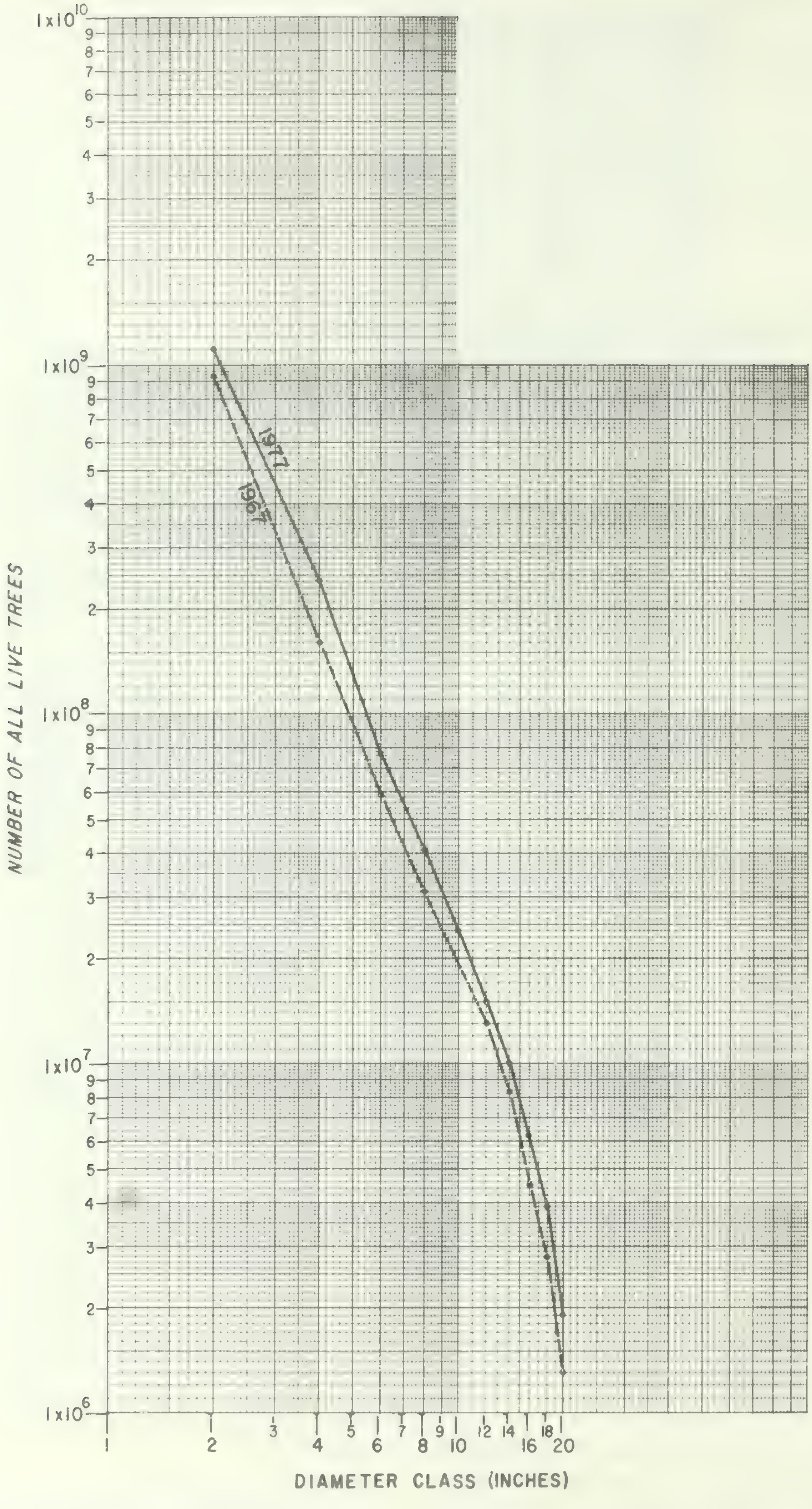

Figure 8.—Distribution of all live hardwood trees on the forest-industry class of ownership in Mississippi, 1967, 1977.

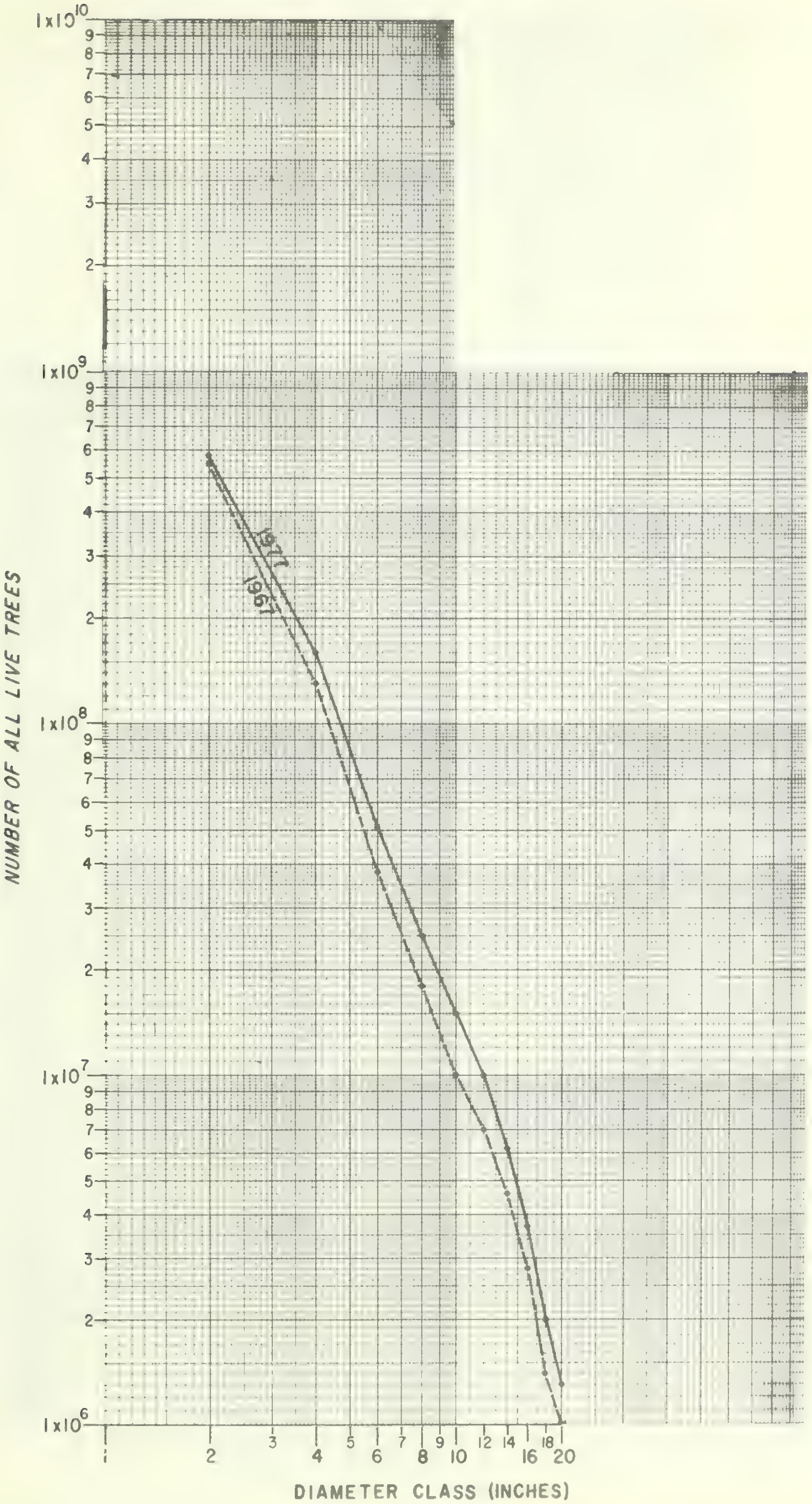

Figure 9.—Distribution of all live hardwood trees on the public class of ownership in Mississippi, 1967, 1977.

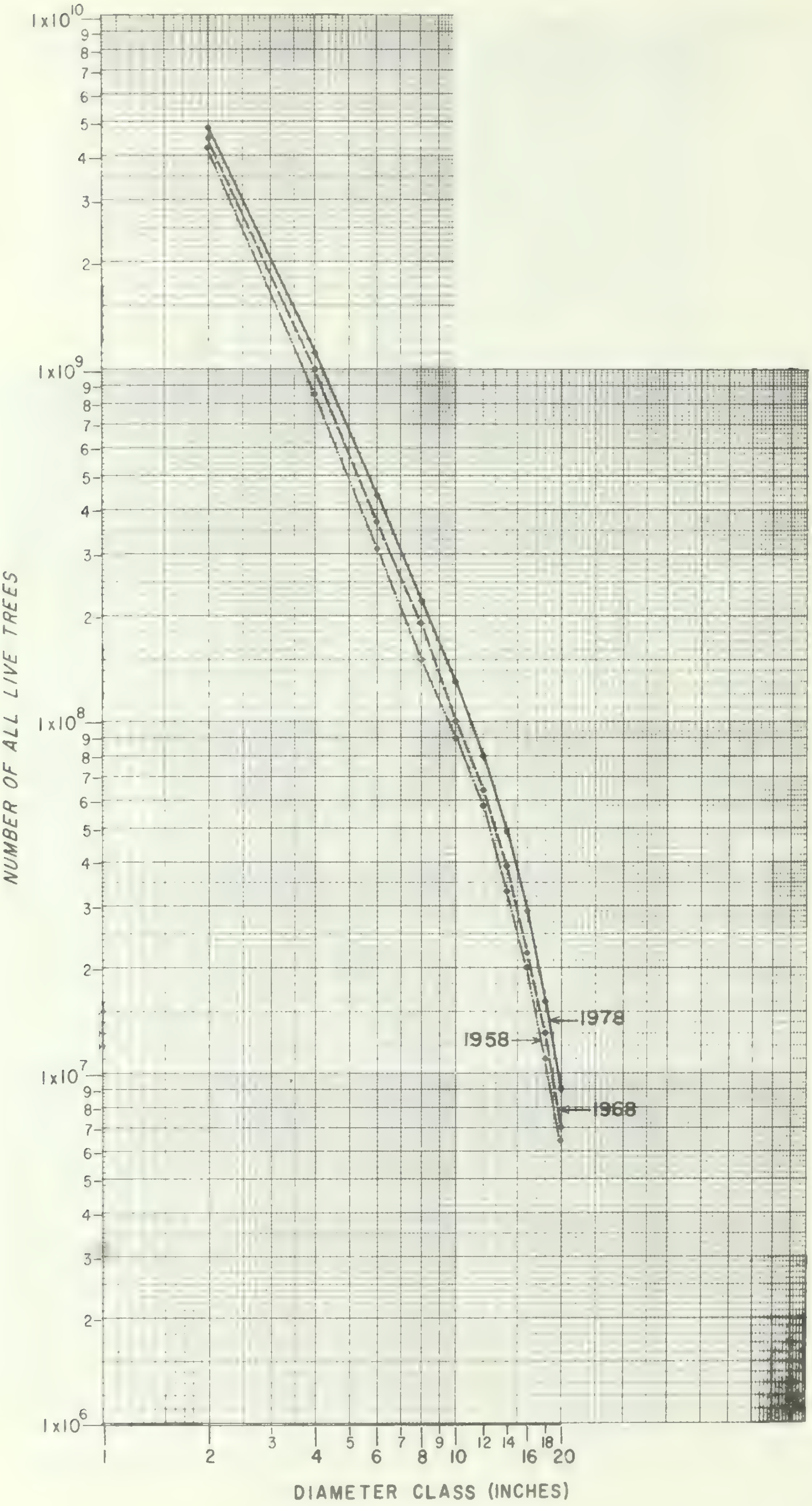

Figure 10.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in South Carolina, 1958, 1968, and 1978.

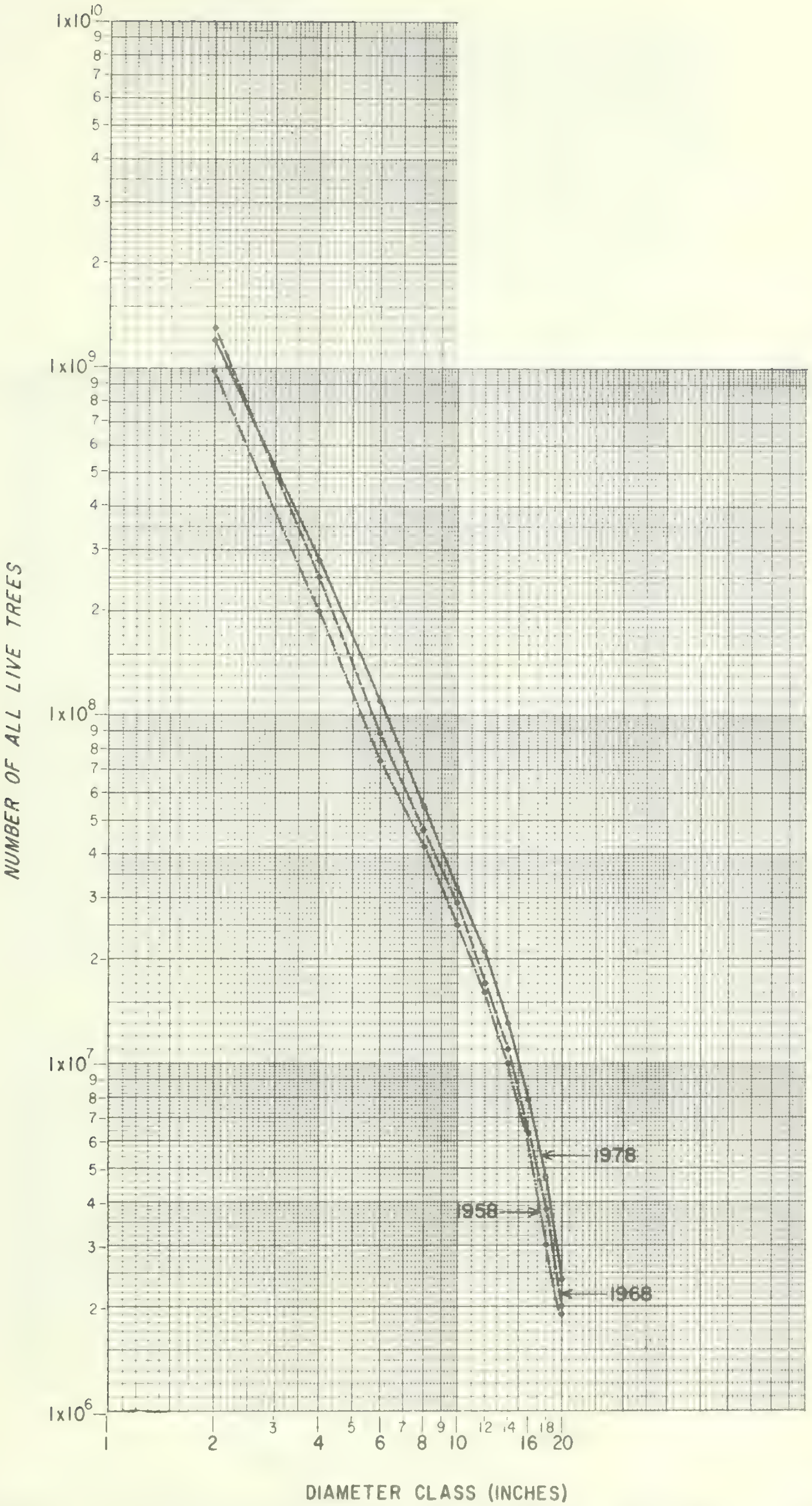

Figure 11.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in the Southern Coastal Plain of South Carolina, 1958, 1967, and 1977.

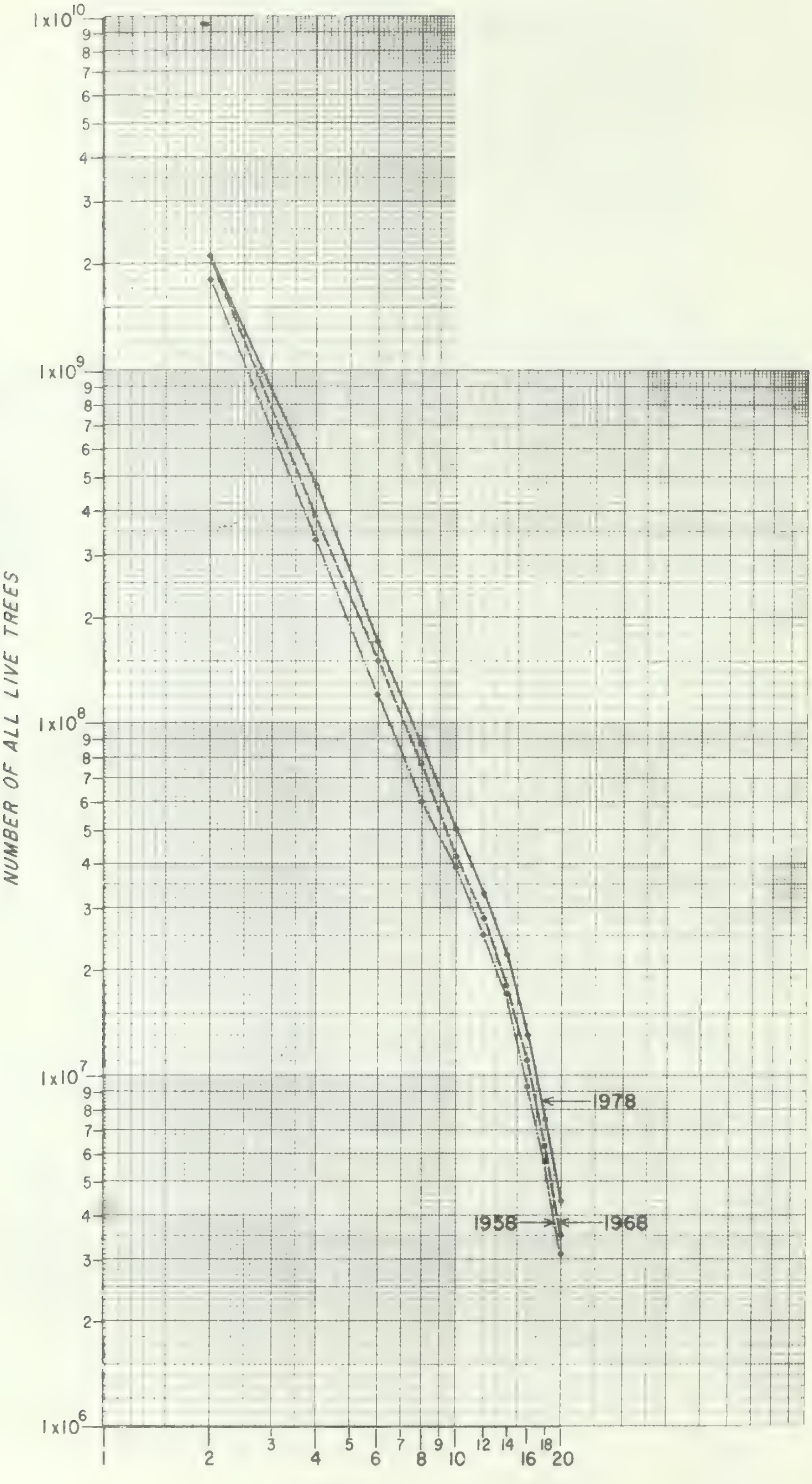

Figure 12.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in the Northern Coastal Plain of South Carolina, 1958, 1968, and 1978.

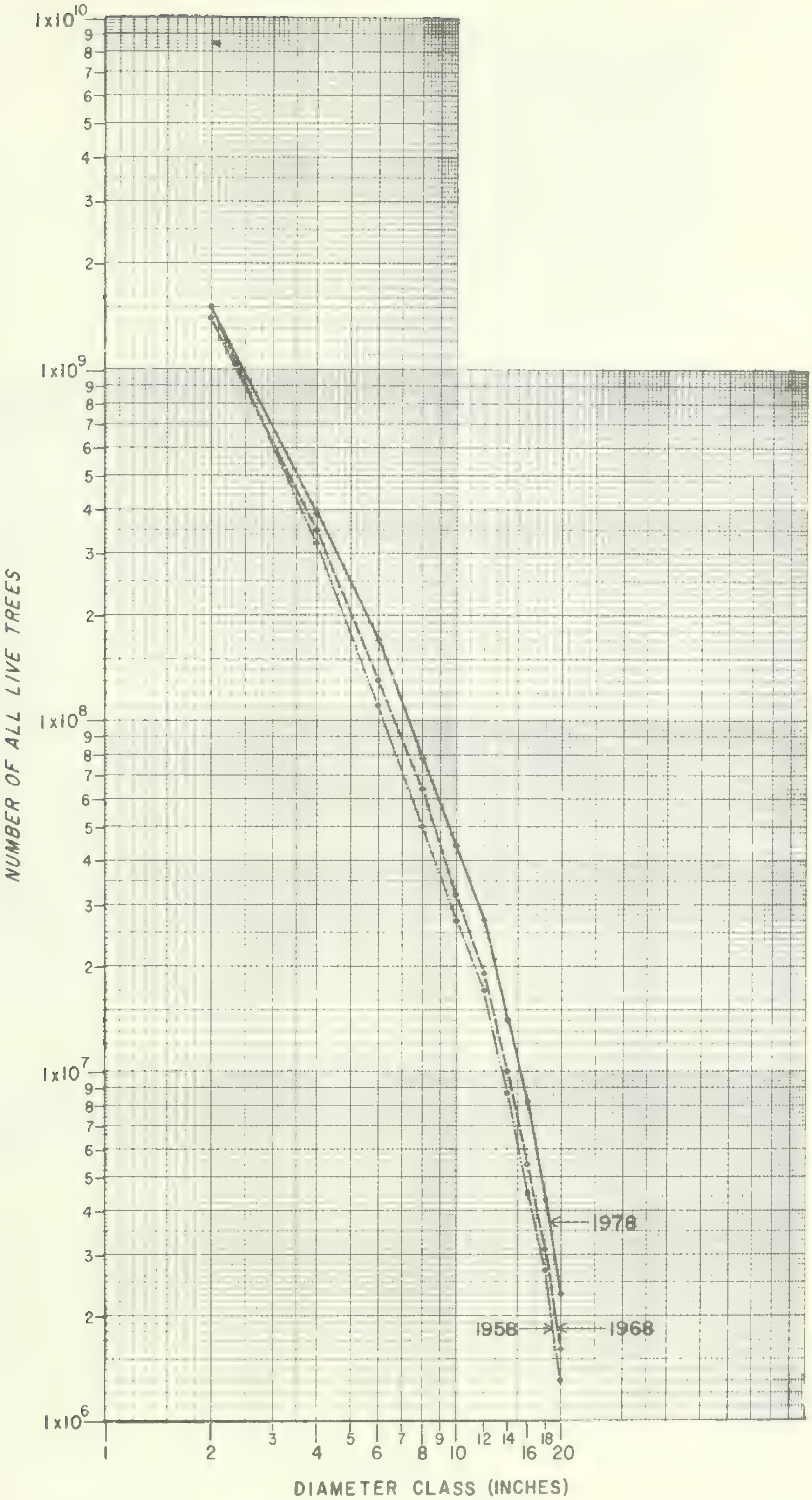

Figure 13.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in the Piedmont of South Carolina, 1958, 1968, and 1978.

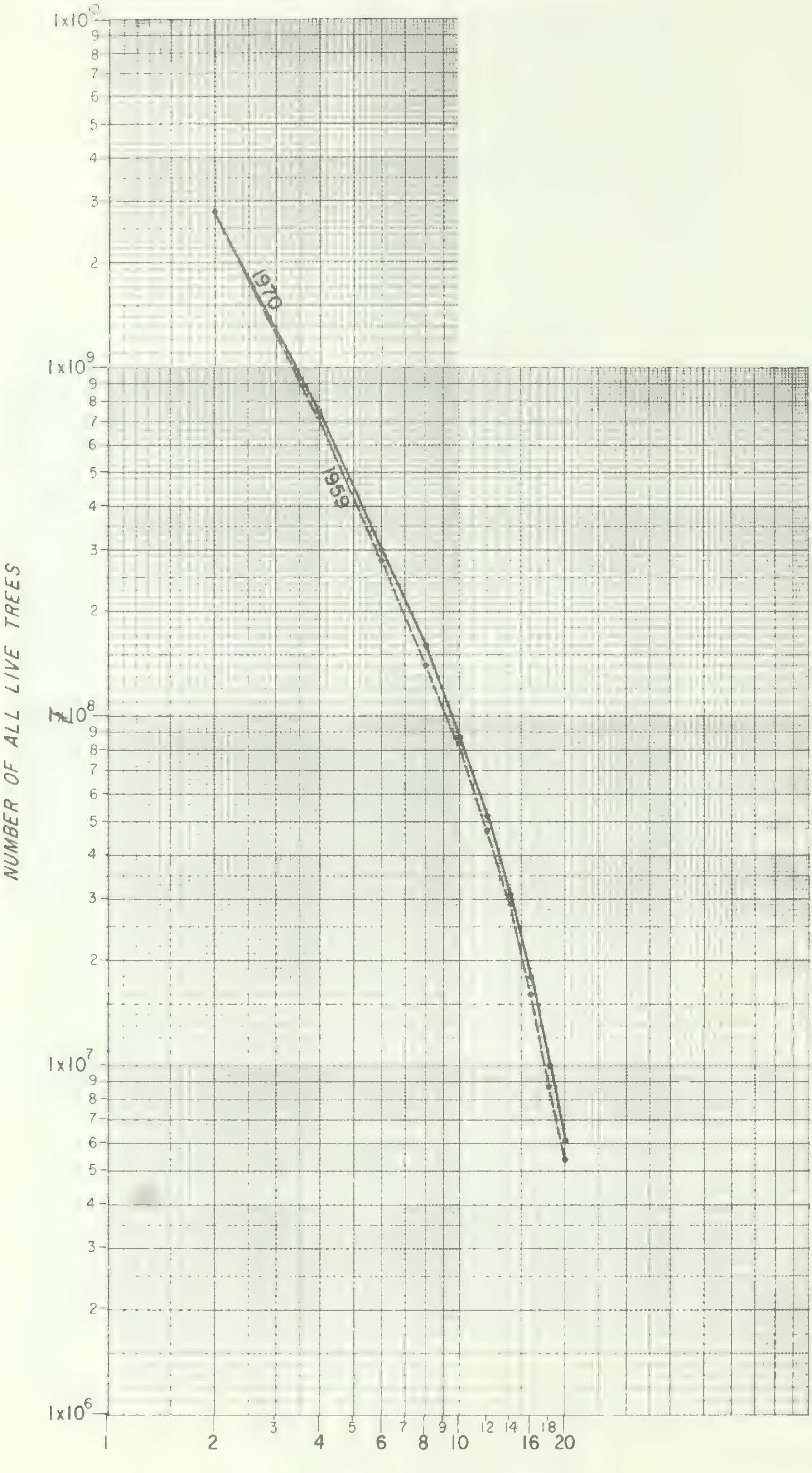

Figure 14.—Distribution of all live hardwood trees on commercial forest land in Florida, 1959, 1970.

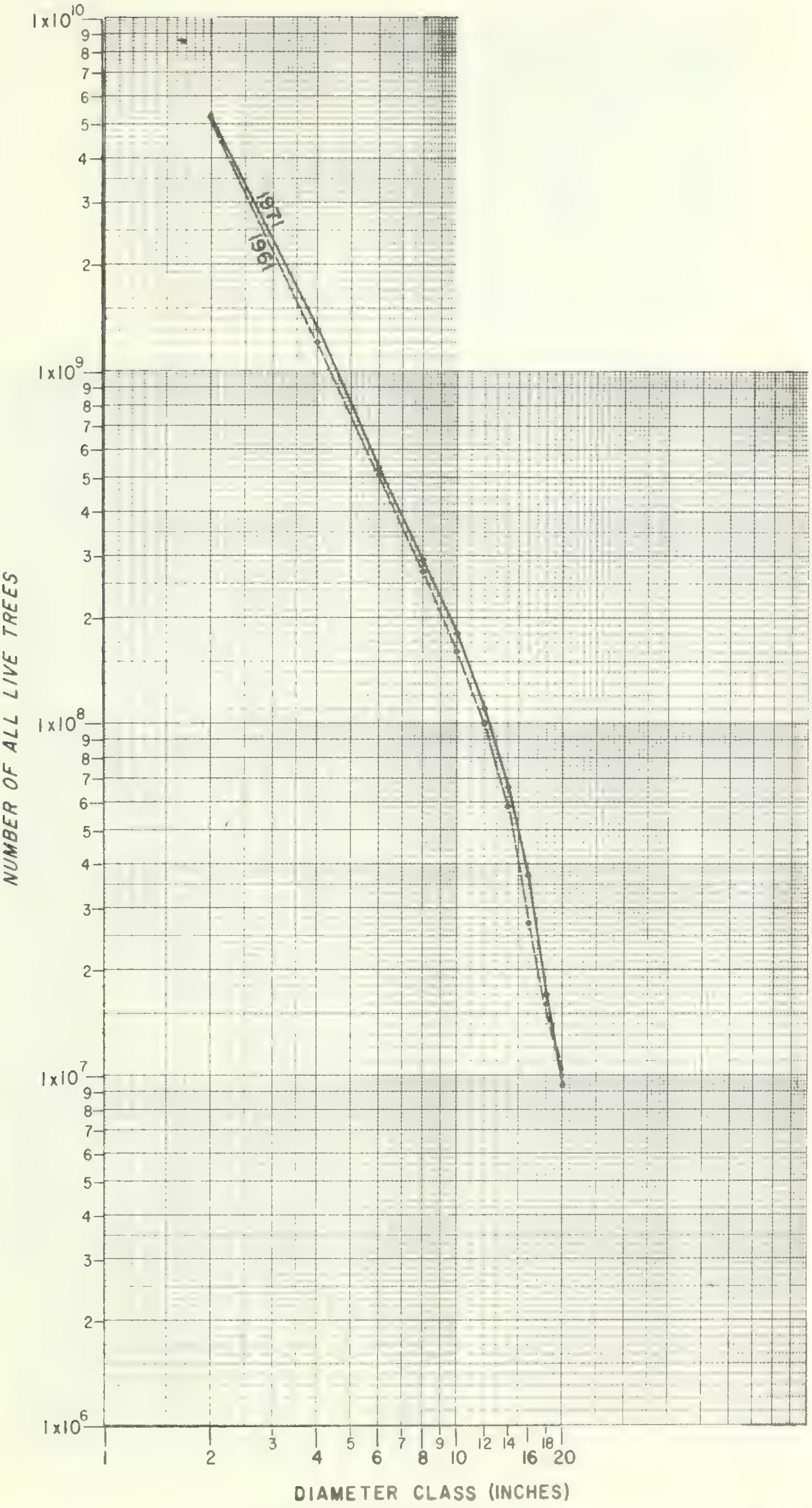

Figure 15.—Distribution of all live hardwood trees on commercial forest land in Tennessee, 1961, 1971.

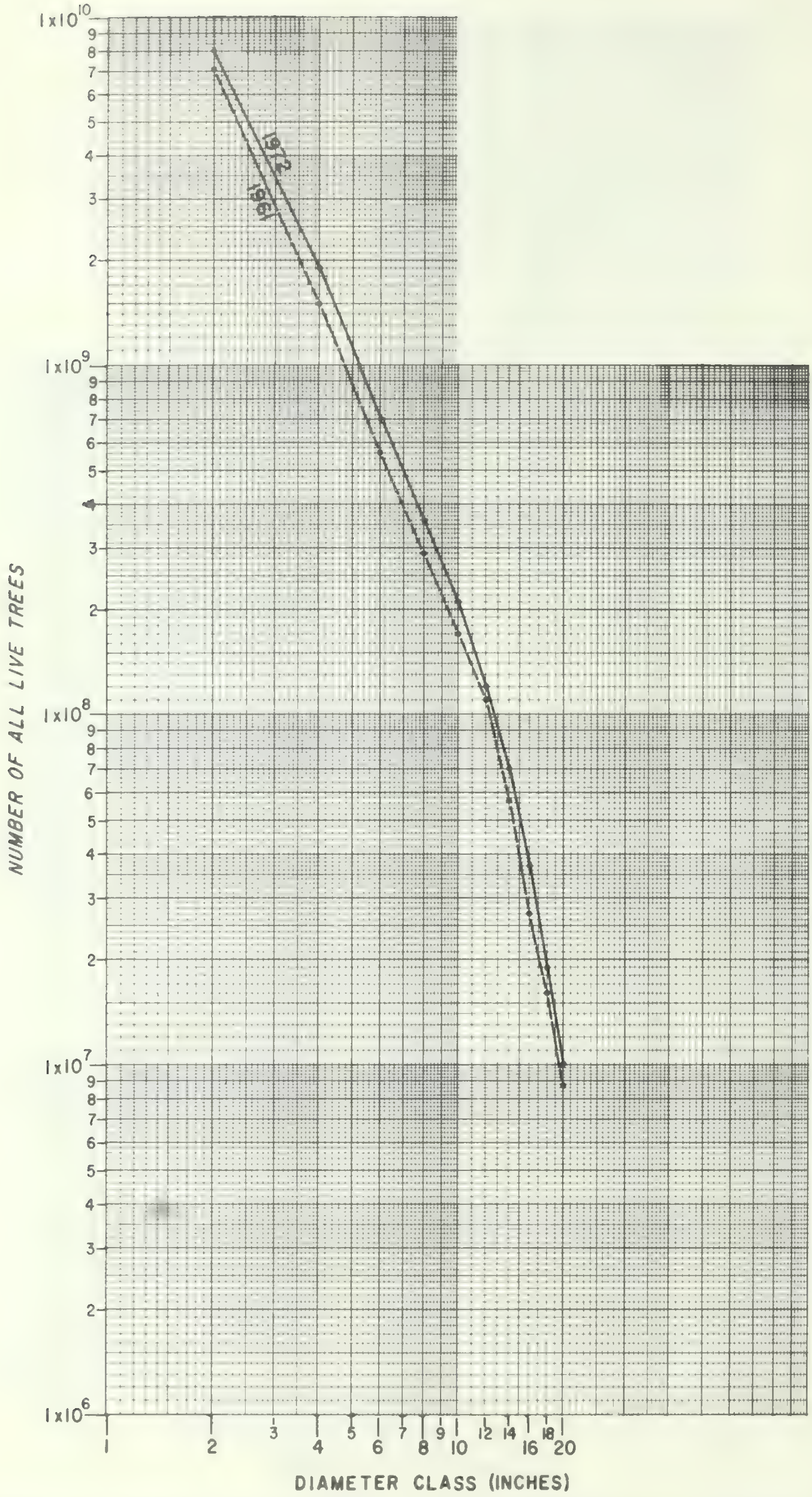

Figure 16.—Distribution of all live hardwood trees on commercial forest land in Georgia, 1961, 1972.

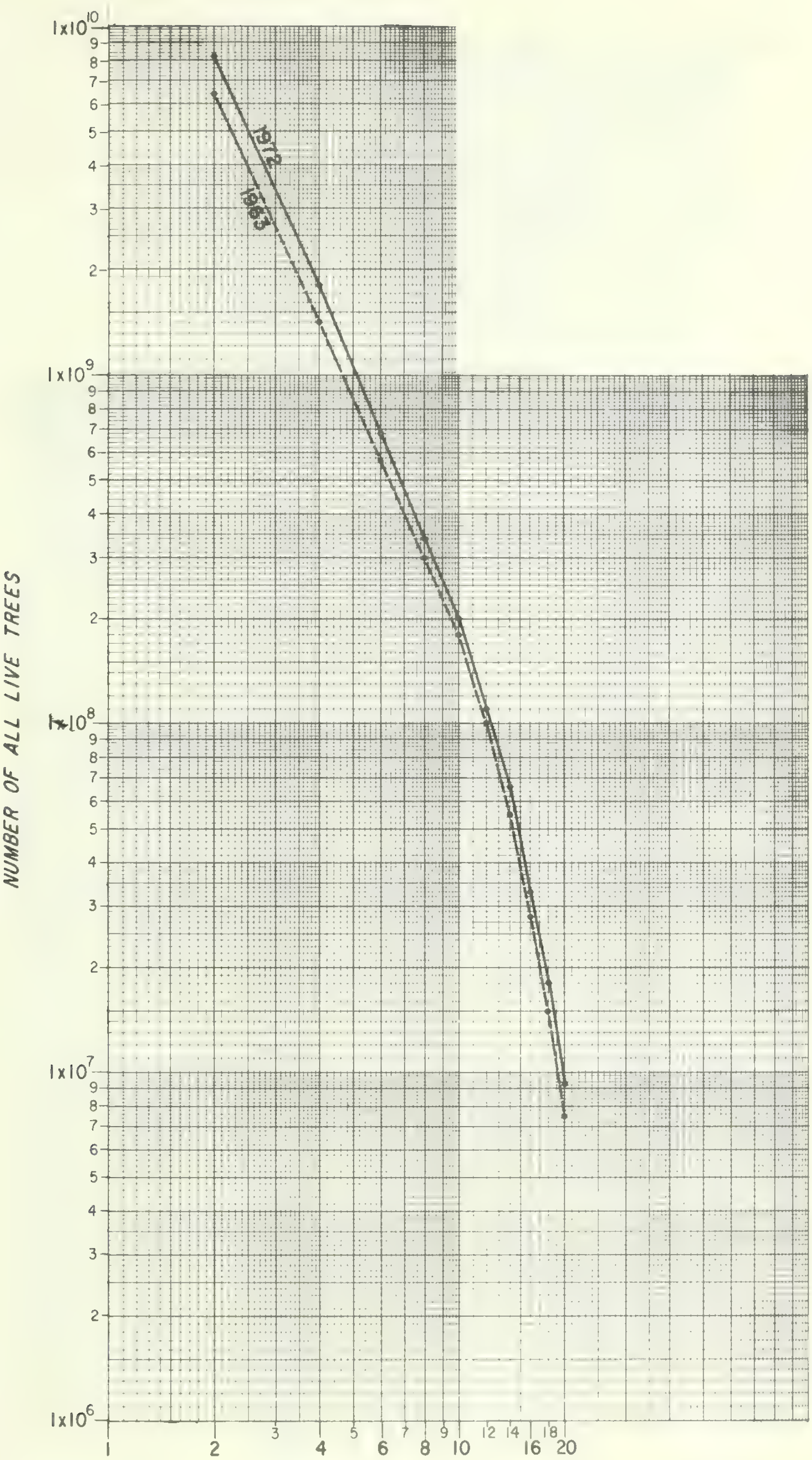

Figure 17.—Distribution of all live hardwood trees on commercial forest land in Alabama, 1963, 1972

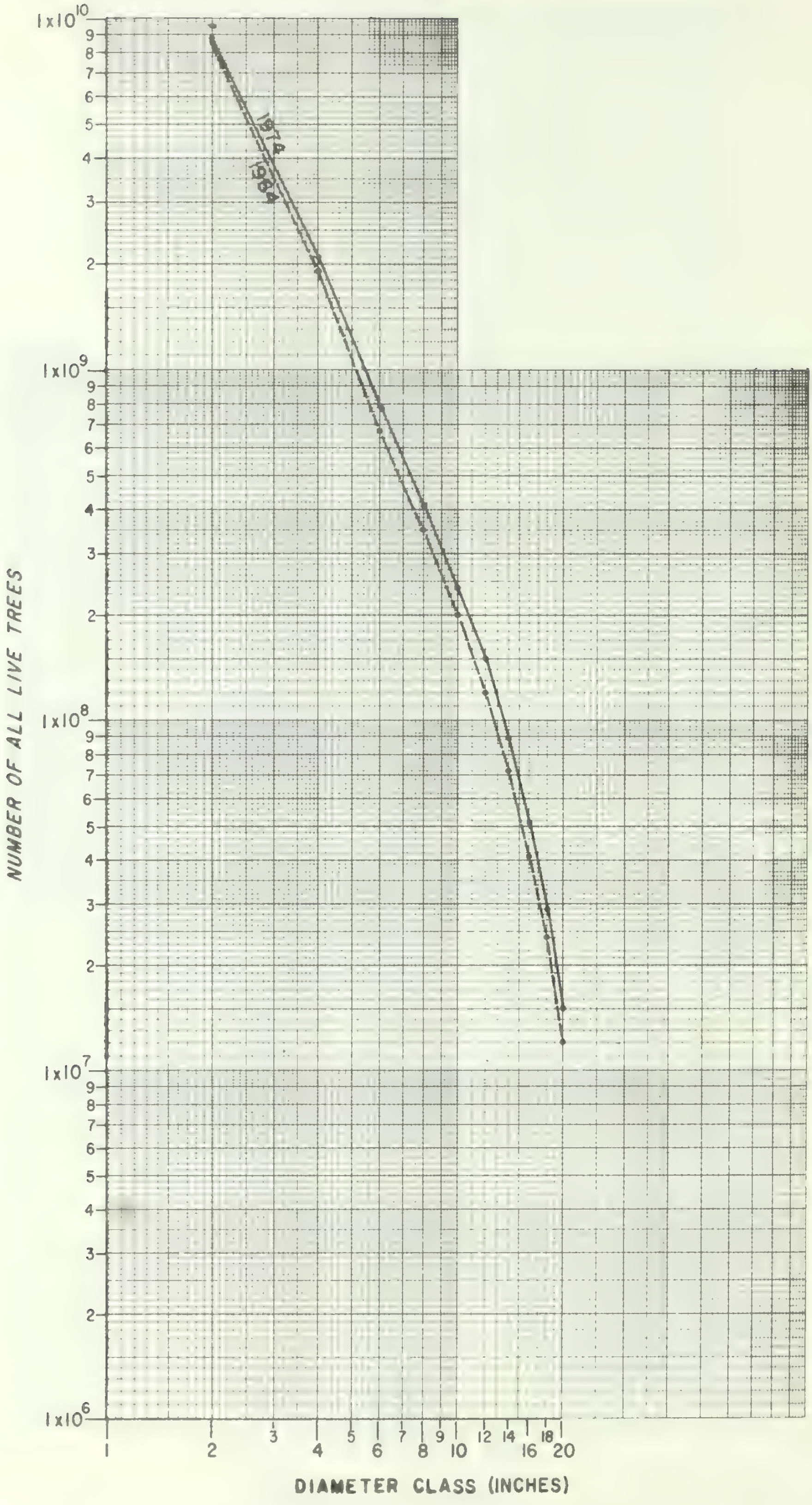

Figure 18.—Distribution of all live hardwood trees on commercial forest land in North Carolina, 1964, 1974.

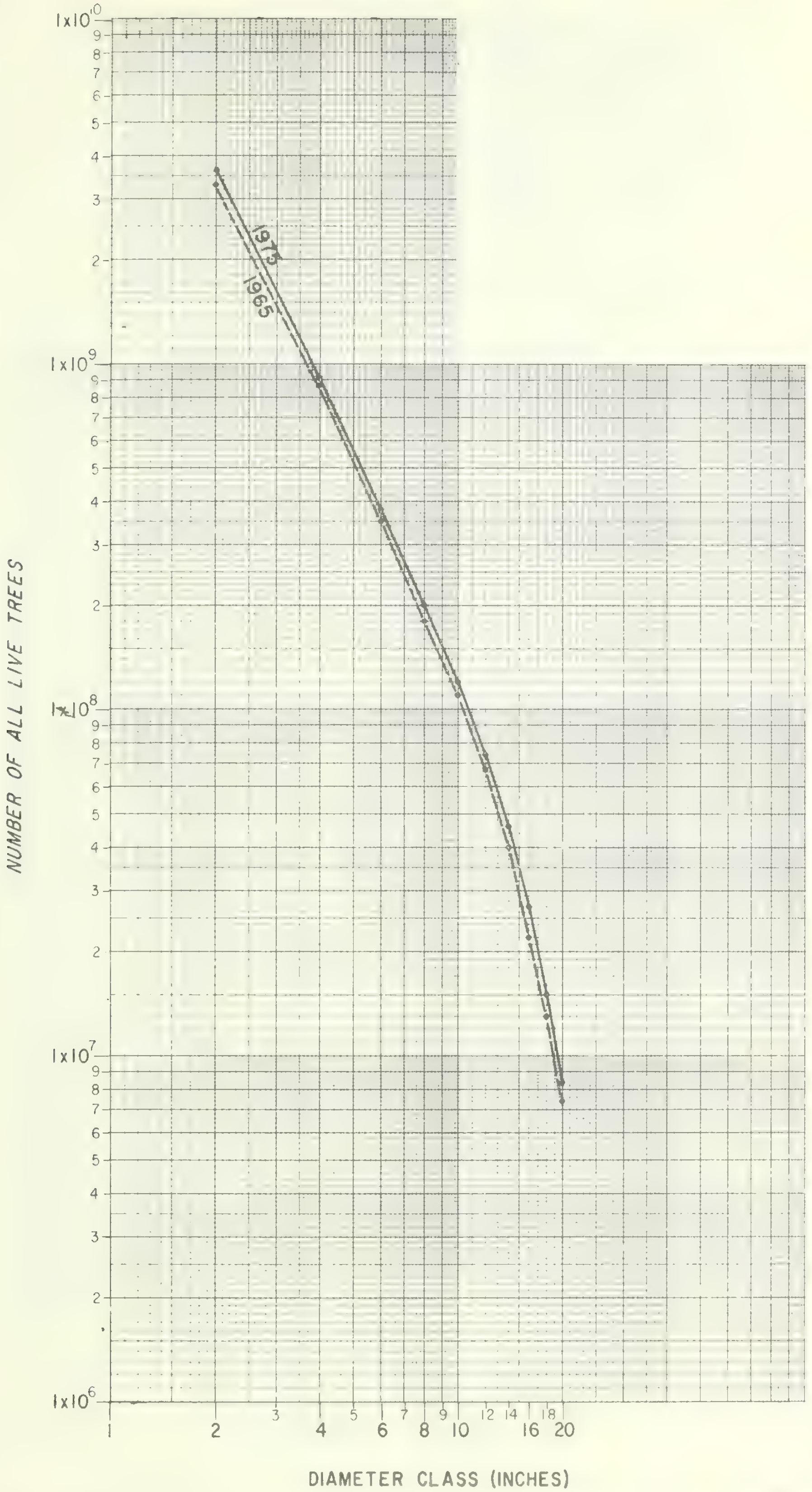

Figure 19.—Distribution of all live hardwood trees on commercial forest land in eastern Texas, 1965, 1975.

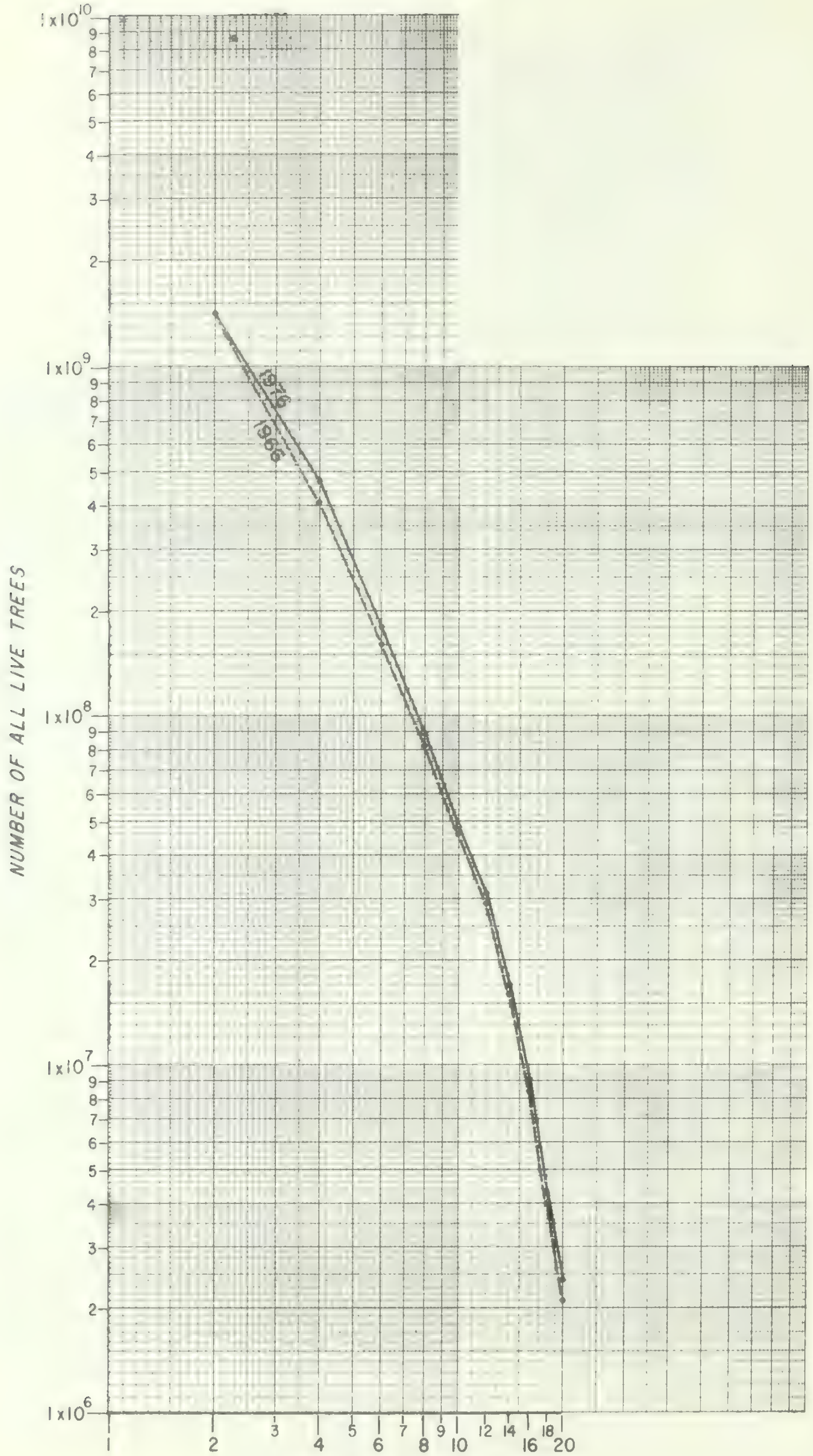

Figure 20.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in Oklahoma, 1966, 1976.

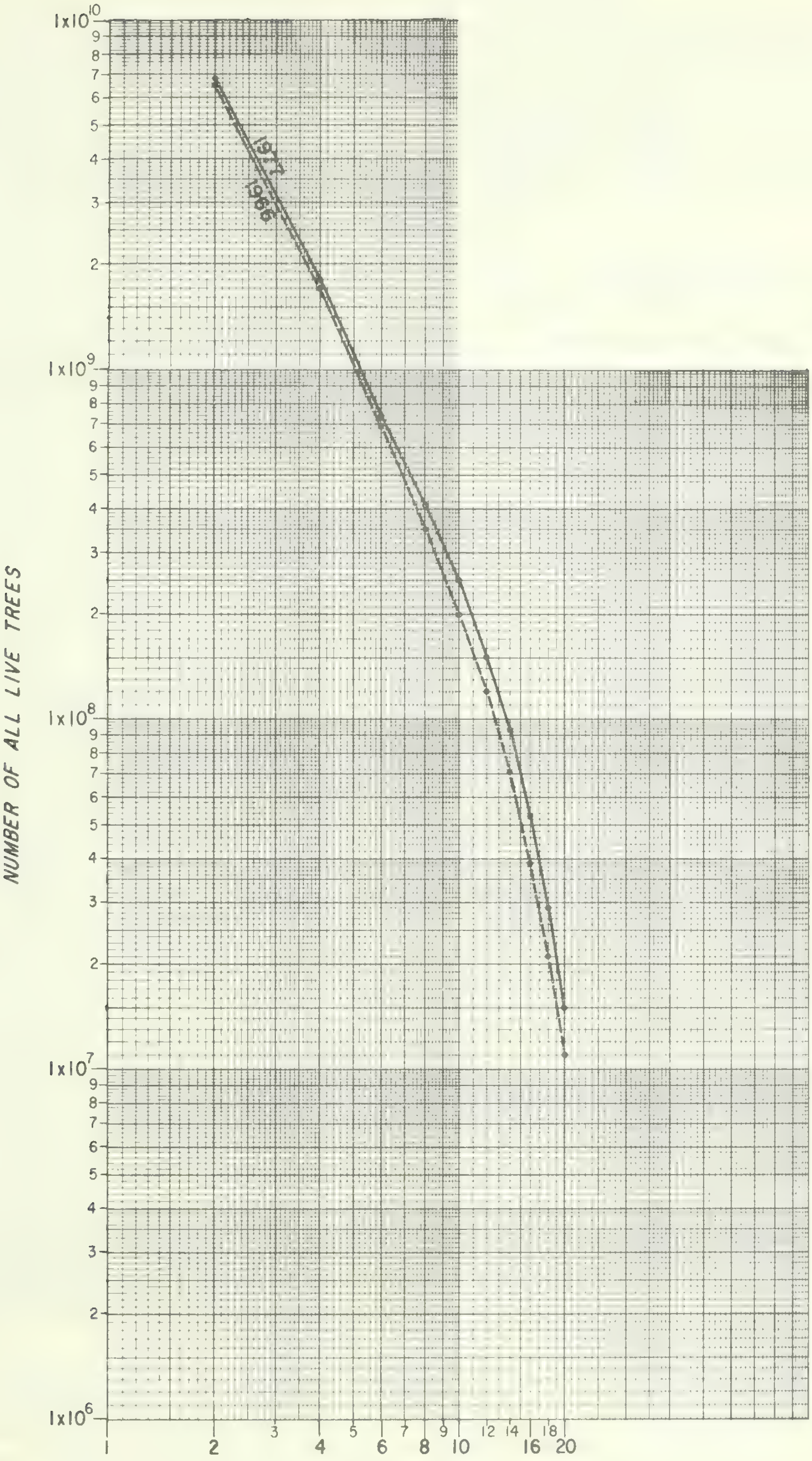

Figure 21.—Distribution of all live hardwood trees, by diameter classes, on commercial forest land in Virginia, 1966, 1977.

Relatively large increases in the potential ingrowth of hardwoods occurred in Georgia, Alabama, and eastern Texas (figs. 16, 17, 19). However, the data provide no indication of future rates of hardwood regeneration and no indication of how the potential for hardwood ingrowth may change.

3.5 Two Important Conclusions

(1) Prospective ingrowth for hardwoods in all 12 States is equal to or greater after than that before 1980.

(2) Investments in cultural practices to favor pines have not been as effective as the forces that favor hardwoods.

In the next section, we examine how the interactions of biological, social, and economic forces influence the potential ingrowth of pines and hardwoods.

4. INTERACTIONS OF BIOLOGICAL, SOCIAL, AND ECONOMIC FORCES

4.1 Biological Forces

The persistence of hardwoods beneath pine overstories and the increase in prospective ingrowth of hardwoods indicate that hardwoods are genetically better adapted than pines for survival in almost all forest environments in the South. This biological advantage of hardwoods over pines results in the replacement of pines by hardwoods on most commercial forest lands.

Almost all pine forests under passive forms of management may be naturally replaced by hardwood forests (Barrett and Downs 1943; Wahlenberg 1960). Most commercial forest lands in the South are passively managed for timber because the majority of landowners do not perceive personal gains in making investments to maintain pine forests after pine timber is harvested (Boyce 1975, 1979; Boyce and Knight 1979b).

4.2 The Effects on Forests of Social and Economic Forces Before 1945

Based on the accounts of early travelers and ecological studies, there seems to be little doubt that the early forests throughout most of the South were predominantly hardwood (Ashe 1915; Wahlenberg 1960; Spurr and Barnes 1973; Brender 1973). Ecological studies indicate that many different mixtures of oaks, hickories, and other hardwoods dominated much of the Piedmont Plateau and the Atlantic and Gulf Coastal Plain (Oosting 1956). Pines were found—some in large stands—but not in the large quantity we know today (Ashe 1915; Wahlenberg 1960). What led to the origin and development of millions of acres of pine forests in this region?

From early settlement until about 1945, it is generally conceded that fire and land use contributed greatly to the establishment and maintenance of pines in the South. Prior to early settlement, American Indians modified the virgin forest by burning the woods for a variety of reasons. The Georgia Piedmont is a classic example of how fire and land use affected the forest (Brender 1973). There, Indians changed the virgin forest by burning to clear lands for cultivation and to improve hunting. Early literature contains decriptions of the species composition in the original forests varying from pure hardwood on red lands, through mixed pine and hardwoods on gray, sandy lands, to predominantly pine on the sandier and drier granitic lands. In a relatively short time, 1773 to 1823, most lands in the Georgia Piedmont were converted from timber to agriculture. But the agriculture was shifting. There was constant cropland retirement and the clearing of "new ground," hardwood stands, for crops. This rotation of land from hardwood forests to crops to retirement resulted in pine spreading and invading many lands previously not in pine. This form of shifting agriculture was essential to maintain crop production because chemical fertilizers and improved agricultural practices were not available.

For more than 100 years in the Georgia Piedmont, shifting agriculture rotated land from hardwoods to crops to pines and back to hardwoods. Pure stands of "old-field pine" became established over extensive areas, especially during three periods of increased rates of cropland retirement: (1) during and after the Civil War, (2) during the agricultural depression of the late 1880's, and (3) after the invasion of the boll weevil in 1920. An estimated 10, 30, and 35 percent of the farmland was abandoned from cultivation during these respective periods.

Wildfires also had an impact on the Piedmont forests. Until about 1940, wildfires burned woods and idle fields frequently, often every year. These fires were beneficial as well as harmful. Small hardwood stems and sprouts were killed, but most of the stumps resprouted. The burned areas were good seedbeds for pine. The combination of reduced growth of hardwood stems and improved seedbeds for pine increased the amount of pine on burned-over areas. Young stands of pine seedlings and advance reproduction were also destroyed over large areas by the uncontrolled wildfires. However, pine trees larger than 4 inches d.b.h. were more resistant to fires than were hardwoods of the same size. The net result was that wildfires favored pines over hardwoods.

Recent data on eastern redcedar reproduction indicate how fire protection is changing the species composition of the forest. Redcedar once occurred as a scattered species because its seedlings are easily killed by fire; high oil content makes the green foliage highly flammable. Prior to 1950, redcedars were much less abundant than today in all parts of the South. For example, in South Carolina between 1968 and 1978, and in Mississippi between 1967 and 1977, there was an increase in the number of redcedars in all diameter classes (figs. 22, 23). Similar increases are found in all 12 States. Fire protection, which is contributing to increased numbers of redcedars, is also contributing to increased numbers of 2- and 4-inch hardwoods.

On the Coastal Plain from New Jersey to Texas, Chapman (1942) largely attributed the origin and maintenance of pine stands to their resistance to fire. (Note that Chapman's paper was written during the period of frequent wildfires.)

As recently as 1931 through 1935, an average of 7.6 million acres of State and private forest land was burned annually in the 12 Southern States (South. For. Resour. Anal. Comm. 1969). For more than 150 years, fire and cropland rotation to forest provided conditions for pine regeneration on millions of acres.

Prior to 1930, shifting agriculture reduced the potential ingrowth for hardwoods and increased that for pine (Greeley and others 1923). The clearing of new ground usually meant the removal of a hardwood stand rather than a pine stand, because the soils under hardwood stands were more fertile for agriculture than those under pine stands (Billings 1938). After a few years the cropland lost fertility. The land would be retired and permitted to naturally regenerate to crabgrass, composites, broomsedge, and eventually, a stand of pines. After 1930, when chemical fertilizers became readily available and rotation of leguminous and nonleguminous crops and the terracing of croplands became common, the rate of shift from forest land to agriculture and back to forest land was greatly reduced. This rotation continues, but on a very much reduced scale in the South (Boyce and McClure 1975).

The first statewide forest inventories began in the early thirties and most of the first survey was completed prior to World War II. When these inventories began, most of the pine timber was second and third growth. Small sawmills and the emerging pulp industry in the South relied upon pine that naturally regenerated on retired cropland.

Even in these early surveys the natural regeneration of hardwood after pine harvests was evident (Oosting 1956). The 1945 reappraisal of the forest situation by the U.S. Forest Service described how harvesting pines allowed hardwoods to dominate areas formerly in pines (USDA FS 1946). The report called attention to counties in the Piedmont of North Carolina, where most of the commercial forest land was covered with small-diameter hardwoods after harvest of the pine and larger hardwoods. Estimates for eight Southern States indicated that total cubic volume of softwood timber had decreased 4 percent since the early thirties, whereas hardwood volume had increased 5 percent.

Large numbers of social and economic changes occurred in the South after 1945. It is this period that we examine in some detail in the next section.

4.3 Social and Economic Forces After 1945

The year 1945 is a significant date for southern pine timber. Veterans who returned to farms in the South bought tractors, and the number of mules declined rapidly. Pastureland needed for the mules was retired and permitted to naturally seed to pine trees. Since many veterans chose not to return to farms in the South, much cropland was retired, and it soon seeded to pine. By 1950 the pulp and paper industry began to manage lands intensively for pines. Many different kinds of industries moved to the South and more people left the farms to work in urban areas. The effects on agriculture of these massive dislocations of labor, capital, and land were apparent (McElveen 1957; USDA Res. Serv. 1957, 1958; Krause 1970). Only recently have these social attitudes and economic forces been recognized as the most-important factors influencing both the present and future availability of hardwood and pine timber (Boyce and others 1975a, 1975b; Boyce and McClure 1976; Boyce and Knight 1979b; Boyce 1979).

After 1945, the States improved fire protection, and forest industries bought land for pine

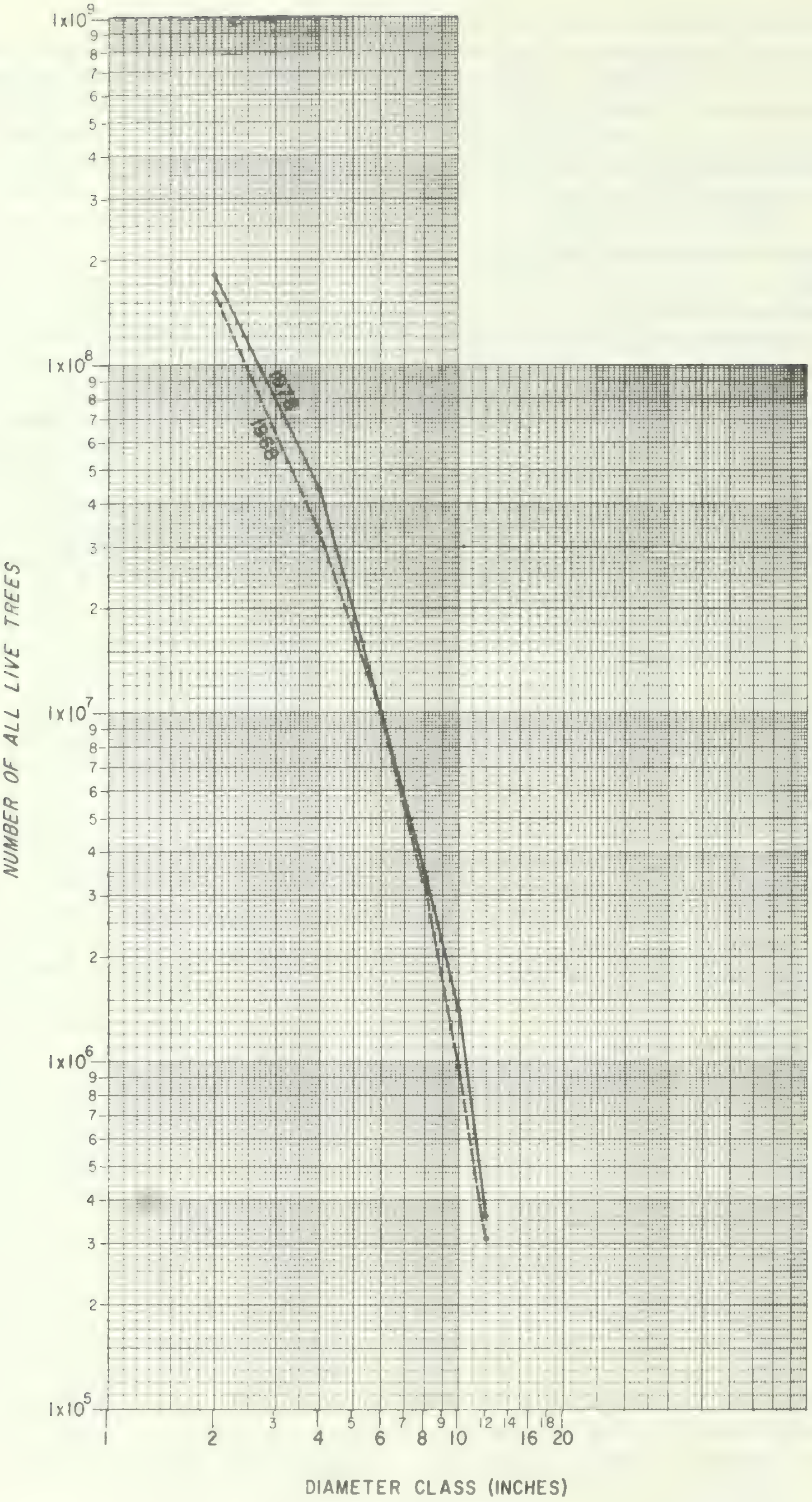

Figure 22.—Distribution of all live eastern redcedar trees, by diameter classes, on commercial forest land in South Carolina, 1968, 1978.

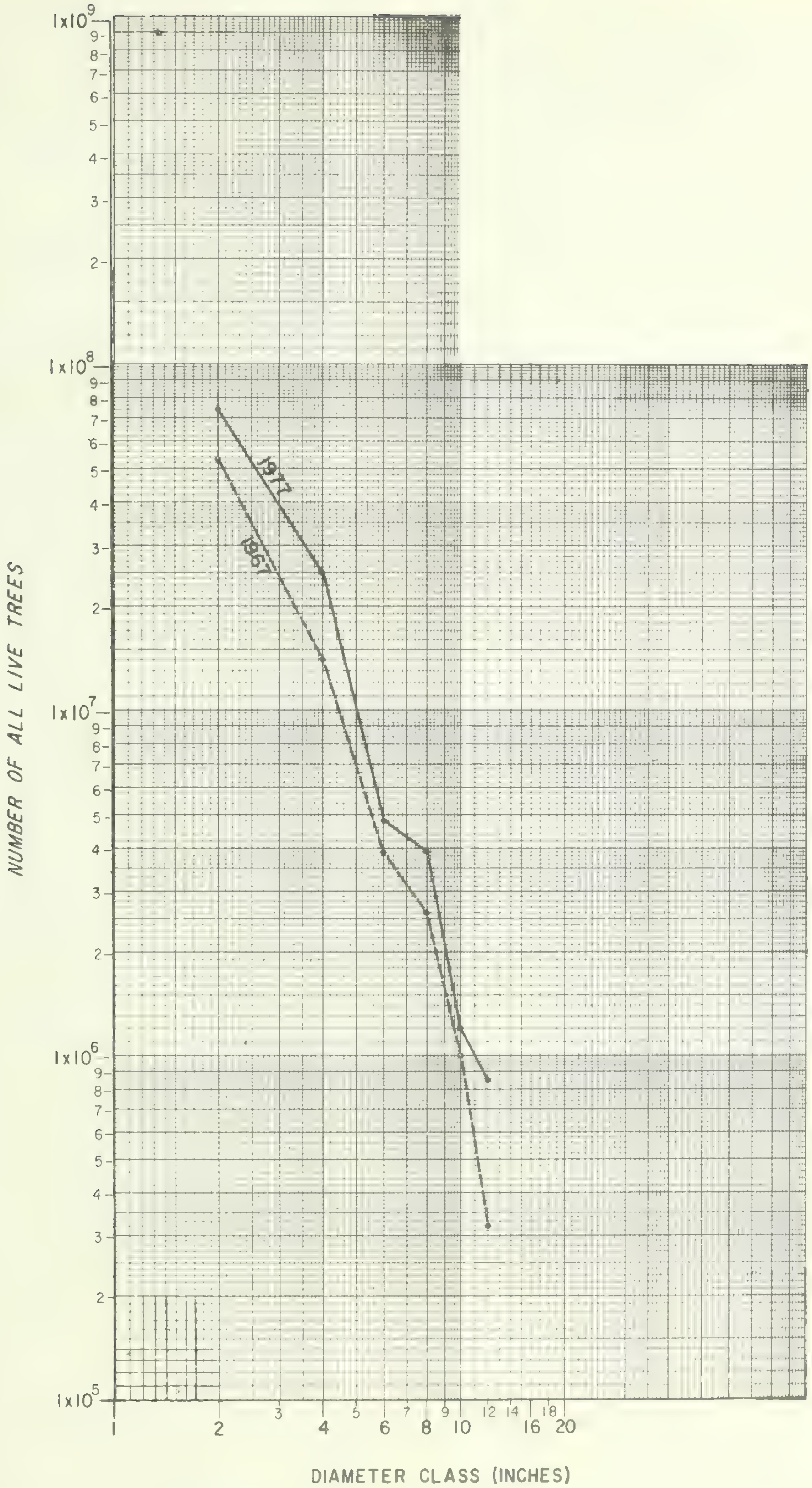

Figure 23.—Distribution of all live eastern redcedar trees, by diameter classes, on commercial forest land in Mississippi, 1967, 1977.

forest. Large capital investments were committed to the use and the perpetuation of pine timber. More and more of the region's forests were brought under fire protection. During the 5-year period from 1941 through 1945, the average annual rate of burn on State and private forests was only half the rate of that from 1931 through 1935 (South. For. Resour. Anal. Comm. 1969). The decline in cropland accelerated as farmers and farm workers moved to urban jobs. With increased use of fertilizer, fewer farmers produced more food on less land. Total acreage available for timber production increased as millions of acres of retired agricultural lands naturally reverted to pine forests. The pine forests were a side effect of major social and economic changes.

About 1949, a number of foresters and resource analysts called attention to hardwood invasion in the understory of pine stands and to a widespread encroachment of hardwoods following the harvesting of pines. After surveying 21 sample counties in the Piedmont of South Carolina, Georgia, and Alabama in 1946, Wahlenberg (1949) found that mixed regeneration may replace any pine stand to some extent. He concluded that pure pine reproduction is definitely assured only where there is a negligible undergrowth of hardwoods. He stated that without cultural assistance "the pines probably cannot reclaim more than half the area being released by present cuttings."

Several foresters cautioned that many of the policies advocated widely at the time—for example, fire exclusion, partial cutting, and many common types of harvest cuttings—were encouraging natural reversion of pine stands to hardwood forest. Haig (1949) and Boyce (1951) both stated that thinnings and improvement cuttings prior to the regeneration cut of a pine stand aggravated the hardwood problem. Boyce (1951) concluded that if a pine canopy is broken by thinnings or other disturbance, hardwoods respond vigorously to the added light and space. Each time a thinning is made, hardwoods gain in stature and extent.

At the same time, Johnson (1949) conceded that a great deal of the forest land in the Virginia Tidewater had reverted to almost pure hardwood stands following the harvest of pines 10 to 50 years previously. He further stated that most pine stands in the Virginia Tidewater have an understory of hardwoods, and that this situation is greatly aggravated in areas where some form of partial cutting has been practiced. There seems to be no form of cutting which, by itself, will assure reproduction of pines in a majority of cases.

At the same forum, Weddell (1949) acknowledged that a considerable area of the Georgia Piedmont was covered with stands of pine or pine in mixture with hardwoods. General observations and statements of many people indicated that hardwoods were invading these stands. He pointed out that a number of cutting methods which had been recommended for pine stands in the area were based on little definite information as to the proper method to follow.

While a number of authors (Ashe 1915; Haig 1949; Chapman 1942; Wahlenberg 1949; Johnson 1949) called attention to the difficulty of perpetuating pine in the South, they may not have envisioned the full effects of social and economic changes on land use and forestry practices. In the wake of a widespread rural-to-urban migration, naturally regenerated pine forests were established on millions of acres of retired agricultural lands over the next 2 decades. Census of Agriculture statistics show that between 1945 and 1964, acreage of cropland harvested in the South declined from 93 to 62 million acres, or by about 33 percent (Krause 1970). While some of this released acreage was diverted to nonforest uses, a substantial but undetermined amount naturally seeded to pine forests. In selected study areas, Knight (1977, 1978) identified a strong correlation between the occurrence of cropland retirement and the age distribution of natural pine stands. A relatively small proportion of these retired croplands was planted to pine (Boyce and others 1975a, 1975b; Boyce and McClure 1976).

During the period of rapid cropland retirement (1945–1965), owners of lands being retired from crops had no capital nor the desire to plant pines. In Georgia and South Carolina, farm incomes declined 25 percent between 1955 and 1956. The acreage of all crops harvested was 5 percent lower in 1956 than in 1955. In 1956, the first year of the Conservation Reserve Program (Soil Bank) about 5 percent of the cotton allotment and smaller amounts of other crops were put into the Soil Bank (USDA Res. Serv. 1957). The annual payments provided under the contracts gave many farmers the capital needed to change to urban jobs.

Within the range of southern yellow pines, some cropland was planted to pines under Soil Bank contracts (USDA Res. Serv. 1958). When entire farms were retired from agriculture, only portions of the land qualified for contracts. Other portions, such as grazing areas, were permitted to naturally seed to pines. The net effect of the Soil

Bank Program in the range of southern yellow pines was to speed the transformation of cropland to natural and planted pine forest.

However, the economic forces and social attitudes toward farming were more important than the Soil Bank in the retirement of cropland (Krause 1970) and in the natural regeneration of the pine forest. Most of the pine stands originating between 1945 and 1965 were the results of social and economic factors. About 2.0 million acres were planted to pine under the Soil Bank Program. This amount represents a small portion of 30 million acres of cropland retired (1945–1964). Most of the pine stands on these lands resulted from natural seeding.

Forest-planting records, however, confirm an abrupt reduction in artificial regeneration on NIPF ownerships in the South following termination of tree planting under the Soil Bank Program. After termination of the program, the average acreage of NIPF lands planted declined and remained at a relatively low rate (Boyce and Knight 1979b).

In contrast to NIPF land, the rate of planting increased on forest-industry land. The area planted in 1957 through 1961 was almost double that planted in the preceding 5-year period. The planted area for the most recent 5-year period, 1972–1976, is, again, about double the rate during the Soil Bank years. With heavy equipment, prescribed burning, and herbicides, forest industries perceive a corporate advantage to intensive pine culture on both retired croplands and on lands in hardwood forests. On the latter lands, clearing, site preparation, artificial planting, and use of genetically superior trees replace partial cutting, long rotations, and natural regeneration. These kinds of investments are essential to maintain pine, since millions of acres of retired cropland are no longer available for natural seeding of pine.

On cutover forest land, in the absence of adequate site preparation and regeneration practices, a number of more recent studies confirm the rate of pine replacement by hardwoods as predicted by Wahlenberg (1949). In 1973, resource analysts determined that half of the hardwood timber in the South was on upland sites currently supporting some yellow pine, or with stumps and other evidence of its former occurrence. Cove-type hardwood sites were excluded (Knight and Murphy 1974). In 1975, a special analysis of the latest survey statistics for Georgia indicated that 54 percent of the acreage of loblolly pine harvested and retained in commercial forest between 1961 and 1972 rotated to another forest type (Boyce and McClure 1975). The latest forest statistics for North Carolina indicate that between 1964 and 1974, hardwoods replaced pines on more than 370,000 acres (Knight and McClure 1975). In Virginia, it was estimated that hardwoods replaced pines at a rate of 53,000 acres per year between 1966 and 1977. Even with the State's Seed-Tree Law and Reforestation of Timberlands Act, it appeared that hardwoods replaced pines on at least 35 percent of the acreage harvested and retained in commercial forest (Knight and McClure 1978). Of 412,000 acres of pine harvested in the Piedmont of South Carolina between 1967 and 1977, only 53 percent remained in pine types (Snyder 1978).

Prior to 1965, these conversions from pine to hardwood stands failed to reduce pine acreage because pine was rapidly occupying retired croplands. After 1965, cropland retirement essentially stopped in most Southern States. Thus, the lack of regeneration to pine of lands from which pine is harvested seems to be the most important factor that is now causing a net decline in rates of pine regeneration

4.4 A Third Important Conclusion

The majority of NIPF landowners, by pursuing their best interest in social and economic situations, passively permit the biologically better adapted hardwoods to increase after the harvest of pines. Thus, on more than 70 percent of the South's forest land, the potential ingrowth for pines and hardwoods, and the future availability of timber, are being determined by biological, social, and economic forces over which the forestry community has little control.

5. IMPLICATIONS FOR THOSE DEPENDENT ON SOUTHERN TIMBER

5.1 Rationalization of the Situation

The biological potential for timber production is the amount of timber expected in a given time with specified cultural practices. In 1975 the harvest of pine timber in the South could have been doubled by regenerating lands from which pine is harvested back to pine (Boyce 1975). This cultural practice is not being used on more than half of the lands from which pine is harvested (Boyce and Knight 1979b). In the context of social attitudes and economic forces, the majority of

NIPF landowners are passively permitting the biologically better adapted hardwoods to naturally increase after the harvest of pine. The consequence is an increase in the biological potential for hardwoods and a decrease for pines.

The influencing social attitudes and economic forces derive from all segments of society, including industrialization of the South, dislocations in agriculture, and attitudes towards the ownership of land. These social and economic forces are not easily redirected. It is unlikely that the social and economic situation will change so that a majority of NIPF owners will perceive short-term, personal gains from regenerating pine on lands from which pine is harvested. Since such investments have never been made by a majority of NIPF owners, it is rational to expect these landowners to continue their passive attitudes toward long-term forestry investments and to sell timber that grows incident to their varied reasons for owning the land.

This rationalization has two important implications for persons and corporations dependent on timber.

5.2 Learn to Use All Kinds of Hardwoods

During the period when growing-stock volumes of pines were increasing (1935–1978), inventions increased the use of small-diameter pine trees, tops, slabs, sawdust, and bark. Now the growth of hardwoods is increasing (table 1), removals are not increasing (table 2), and potential

Table 1.—Trends in net annual growth of hardwood growing stock on commercial forest land in the South, by region, 1952–1976[1]

Region[2]	Year			
	1952	1962	1970	1976
	Thousand cubic feet			
South Atlantic	862,716	1,004,582	1,307,726	1,483,163
East Gulf	428,902	463,487	524,472	603,519
Central Gulf	864,500	983,200	1,172,396	1,354,319
West Gulf	666,700	682,000	966,039	1,114,726
Total South	2,822,818	3,133,269	3,970,633	4,555,727

[1] From U.S. Dep. Agric., For. Serv., 1978.

[2] See table 2 for States in the regions.

Table 2.—Trends in annual removals of hardwood growing stock on commercial forest land in the South, by region, 1952–1976[1]

Region[2]	Year			
	1952	1962	1970	1976
	Thousand cubic feet			
South Atlantic	650,000	676,900	741,070	683,054
East Gulf	363,900	375,597	318,004	319,467
Central Gulf	849,700	846,400	724,792	621,238
West Gulf	699,500	814,200	948,994	476,380
Total South	2,563,100	2,713,097	2,732,860	2,100,139

[1] From U.S. Dep. Agric., For. Serv., 1978.

[2] States included in the regions are South Atlantic (Virginia, North Carolina, South Carolina), East Gulf (Georgia, Florida), Central Gulf (Alabama, Mississippi, Tennessee), and West Gulf (Louisiana, Arkansas, Oklahoma, Texas)

ingrowth is increasing (sec. 3). The rational response is to invent more ways to use all kinds of hardwoods for marketable products, including many now made from pines.

Greater marketability created by new uses for hardwoods could increase the rate of harvest from NIPF ownerships. However, this alone is not enough to encourage most of these landowners to make long-term investments in growing timber. The economic returns for growing trees to market as stumpage will probably remain low relative to other investment opportunities. Increased marketability of hardwoods would simply increase the opportunity to use the sort of timber that most landowners are likely to produce.

5.3 Keep Commercial Forest Lands in Timber Production

During the period of rapid dislocations in agriculture (1945–1965), the conversion of commercial forest lands to urban uses was offset by cropland retirement. There was a net increase in the area of commercial forest land (table 3). Since cropland retirement essentially stopped, about 1965, the area of commercial forest land has been decreasing. Continued conversions of about 500,000 to 600,000 acres per year (table 3) could, in a relatively few decades, reduce the biological potential for timber, wildlife, game, esthetic values, and other forest benefits.

Most NIPF lands remain in forest not because the owner is planning to sell timber but because of other motives. Most timber harvested from NIPF lands appeared and grew as a side effect of other activities and investments of the owner. Some hold their land for long-term capital gain, others for recreation, and still others for esthetic and emotional satisfaction. Thus, the continued maintenance of timber production on a large portion of the South's commercial forest land depends on the use of timber harvesting to enhance the value of multiple benefits to NIPF owners.

This Paper is not the place to describe the details for achieving this end, but certain requirements can be identified. The harvest of timber must be arranged to return more benefits for the landowners than just the value of the stumpage. The costs of harvesting must be paid by the purchaser of the timber, and the act of harvesting must provide for regeneration at little or no cost to the landowners. As an additional bonus for encouraging harvest, patterns of harvest must be arranged that enhance the value of the land in relation to the landowner's motives for holding it.

The goals of low-cost management and enhanced nontimber benefits are attained most effectively by natural regeneration and by regulating the rates of harvest and the sizes of areas harvested to bring about a desired organization of the forest (Boyce 1977). This proposal is consistent with the historical and biological evidence that timber production on most NIPF ownerships is incident to nontimber-producing activities. The proposal is congruent with the social and economic forces that influence NIPF landowners to perceive which forestry investments are in their best interest.

Table 3.—Trends in area of commercial forest land in the South, by region, 1952–1977[1]

Region[2]	Year			
	1952	1962	1970	1977
	Thousand acres			
South Atlantic	46,963	47,912	48,463	47,677
East Gulf	42,104	43,128	41,334	40,142
Central Gulf	49,497	53,361	51,454	51,045
West Gulf	53,519	55,505	51,291	49,569
Total	192,083	199,906	192,542	188,433

[1] From U.S. Dep. Agric., For. Serv., 1978.

[2] See table 2 for States included in the regions.

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KEYWORDS: Southern hardwoods, ingrowth, natural regeneration.

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Management of Forests for Optimal Benefits (Dynast-OB)

by

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ABSTRACT.--A new process can assist forest management to provide selected optimal forest benefits in perpetuity. A system dynamics technique, DYNAST-OB, is the mechanical method for quantifying and interrelating different kinds of forest benefits. This model has the capacity to integrate management strategy and tactics for a complex forest area divided into types or categories. The model and its use are described.

Keywords: Multiple benefits, silviculture, system dynamics, cybernetics, timber, wildlife, watershed, diversity.

1. INTRODUCTION

1.1 Purpose for this Paper

Biological knowledge and mathematical techniques can be joined to point a new direction for forestry, harmonizing management actions to provide a chosen combination of biologically possible benefits (Boyce 1978b). Many forests, especially those in public ownership, are managed for multiple benefits (Boyce 1977). Other forests are managed primarily for timber, with some concern for the available related benefits (Boyce 1978a). However, many relatively large forest areas will be managed according to laws, directives, profit incentives, and public concerns which dictate the optimizing of one particular benefit, such as timber, wilderness, increased water yield, or habitat for a particular animal or plant (Boyce and Cost 1978).

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Analytic techniques have not been previously available for assessing, over time, the consequences of these different strategies (Levin 1974). For example, if the wilderness state of organization is considered optimum for a forest, how does this form of management, over time, affect the availability of human benefits and the livelihood of endemic organisms? If one is concerned primarily with increased water yield, how do the management actions which yield the most water affect other benefits? If one is concerned chiefly with providing optimal habitat for squirrels and black bear, what are the consequences of maintaining these states of forest organization? Can more than one benefit be optimized within a particular forest?

In this Paper, I illustrate how the planning model DYNAST-OB is used to answer these questions. I describe how the model is used in planning the management of forests for an optimal benefit, in predicting the consequences of optimizing one benefit, and in selecting a mode of management for any combination of benefits that is biologically possible.

1.2 An Overview of the Presentation

Chapter 2 explains the planning process for providing optimal forest benefits in perpetuity. This chapter discusses the relation of the optimal benefit or group of benefits to the biologically possible states of organization of the forest and explains why the goal for cultural actions is to bring about the particular state of forest organization that provides the desired optimum.

Chapter 3 illustrates five modes of management that have been selected to bring about a desired optimum. The illustrations demonstrate the flexibility and the usefulness of the model for many different purposes for management.

Chapter 4 is a technical description of the mathematical model, showing how the two types of equations used are related and how they function to project the state of organization of the forest and the associated benefits. I describe how the system's controls can be used to answer questions for the planning process and how the model is applied to multiple forest types or other categories.

2. NATURE AND FUNCTION OF THE PLANNING PROCESS

2.1 Optimums as Subjective Perceptions

Optimums are subjective perceptions of the most favorable conditions for a given situation. Most of us use information to make decisions that we perceive to be optimum. For example, one person may believe that wilderness conditions provide optimal benefits from a given forest. Another person may see the combination of opportunities to camp, hike, hunt, and fish as optimum. And still another may perceive the production of furniture, houses, and paper as the optimal benefit. Regardless of the optimal benefit perceived, a managed forest requires plans that can be used to schedule and direct cultural actions. The purpose of these cultural actions is to bring the forest to the desired state of forest organization (sec. 2.3).

The state of forest organization is measured by the distribution of stands by forest types, age classes, and area. A class of stand, conveniently called habitat, is described by its dominant species or type, age, and area. As the stands within a forest age, they evolve through habitat classes, changing the state of forest organization.

2.2 Optimums Result from States of Forest Organization

Each state of forest organization provides a particular combination of biologically possible benefits. For example, the availability of timber over time is determined by the proportional distribution of seedlings, saplings, poles, and mature timber stands. These stand classes, viewed as habitats and distributed in different combinations of sizes and locations, determine the livelihood of plants and animals, the production of timber, the flow of water and nutrients, the esthetic values, and the opportunities for hunting and fishing.

Knowledge about these relationships provides a way to use planning models for assessing the consequences of management for different optimums. The planning model, when congruent with the real forest, provides a way to assess the biologically possible modes of management "on paper" without actually taking the forest through the states of organization that may be indicated by different perceived optimums. The model, the computer, and the charts are simply mechanisms that interrelate and communicate our knowledge about the behavior of individualistic systems (Boyce 1977) in the real forest. The mental models of large numbers of scientists and managers are interrelated in the DYNAST models.

By manipulating the model, changing rates of harvest and sizes of openings, we can find out which different combinations of benefits are available at different states of organization. We can follow the changing patterns of benefits as the forest changes from the original inventory to a desired state of organization. We can choose the mode of management that most nearly fits our perception of an optimal benefit, then use the planning model to guide implementation.

2.3 A State of Organization is the Goal for Cultural Actions

Traditional forest management is most successful when it seeks to maximize one primary benefit such as timber, water, or a wildlife habitat and permits other benefits to vary with the primary benefit. The difficulty created by demands for multiple benefits is to resolve conflicts in management actions when two or more primary benefits are sought; there is a major problem in translating goal statements into a harmonized program of actions. Since one can direct harmonized actions toward only one thing at a time, an obvious solution is to find a single goal toward which management actions can be directed. That goal can be defined as a certain state of forest organization (fig. 1).

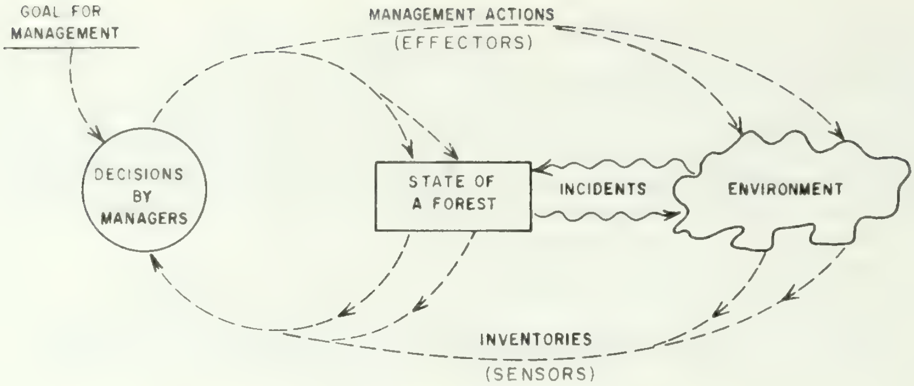

Figure 1.--This generalized diagram illustrates how a state of forest organization is made a single goal for cultural actions (Boyce 1978b).

The diagram in figure 1 could represent the ordinary processes of forest management, whenever they are pursued with some degree of awareness and foresight. However, in the system advocated here, these processes are enhanced significantly. First, the goal for management is selected after forecasting the behavior of the forest by running the model to simulate different policies of management. In this way, the consequences of managing for an optimal benefit can be understood, and the most desirable combination of benefits that is biologically possible can be selected.

Then the goal for management is defined as a state of forest organization that provides this combination of benefits; management actions are guided by this goal; and inventories feed information back into the decision process to keep the system on track. The organization of the forest (the distribution of habitats) is controlled by scheduling the rates of harvesting (Boyce 1977, 1978a). Two or more rotation periods may be superimposed so that old growth and young stands are closely intermingled and, over time, interchangeable. Thus, age classes of stands are distributed in varying proportions. The distribution of habitats is brought to one of the many possible steady states.

2.4 Strategic Plans

The strategy for management is to determine the purpose for which a particular forest is to be managed. One purpose could be to provide as much timber as possible with minimum concern for related benefits. A single rotation period is necessary to achieve maximum production of timber. In this case, the appropriate planning model for determining the state of organization would be DYNAST-TM (Boyce 1978a).

Another purpose could be to provide biologically possible combinations of benefits. For this purpose, two superimposed rotation periods are necessary to bring about the necessary states of forest organization. The appropriate planning model would be DYNAST-MB (Boyce 1977).

A third purpose could be to maximize a particular benefit. A benefit which management has selected to be so favored is here called an optimum. Some examples of optimums are wilderness, habitat for an endangered species, timber, water, and game habitats. Optimal use of a forest could further involve designating a combination of separate areas, each to be used for a different purpose, such as wilderness, timber, or water production. For determining the state of organization in these cases, the appropriate planning model would be DYNAST-OB, which is described in this Paper. DYNAST-OB can also handle the simpler tasks for which the other models were designed. Its distinctive capacity is the power to coordinate different management strategies when a forest is divided into areas designated for different uses.

2.5 Tactical Plans

Tactical planning involves the selection of a mode of management once the strategy, in this Paper the choice of an optimum, has been determined. The DYNAST models are used to display the combinations of benefits resulting from the use of different modes of management. Thus, the choice of a biologically possible combination of benefits determines the mode of management. Implementation of the indicated mode of management should provide the desired benefits if the model is based on theories that are not falsified by behavior of the real forest (Boyce 1978b).

All three models, DYNAST-MB, DYNAST-TM, and DYNAST-OB, are based on the same biological theories. The theories provide the basis for understanding natural changes in the forest and for taking actions to bring about desired states of organization (Boyce 1978b). The dynamics of these changes are the cores of the DYNAST models (fig. 2). Openings, formed by the harvest of timber and by natural mortality, are naturally or artificially regenerated to trees that form new stands. These new stands successively transform from one kind of habitat to another and thus determine the dynamic state of organization of the forest.

Different modes of management are determined by changing the size of openings formed by harvesting and by changing the rates of harvest of trees. Openings are the spaces vacated by the death or removal of trees. The area of each canopy opening determines the area of each succeeding stand. Rates of harvest are measures of the total area of canopy openings formed per year. These variables are called here the analytic silviculture controls.

Different analytic silviculture controls are used in computer model runs to project the states of organization of the forest into the future. Benefits are displayed for each state of organization. From these displays one can choose the mode of management that most nearly orders the combination of benefits perceived to be optimum.

2.6 Technical Plans

Cultural actions based on technical knowledge are scheduled to achieve the goals of management.

One action, the harvest of a certain area of forest land from each of the kinds of stands, is computed and printed by the model. This rate of harvest and the range of sizes of openings formed by harvest are determined by the analytic silviculture controls. These controls simply specify the age for harvest of each habitat, the proportion of forest that is to succeed through each habitat, and the sizes of openings. For example, all the analytic silviculture controls are set at 0 for the management mode designated "optimal wilderness" (table 1).

Table 1.--The analytic silviculture controls for the mode of management designated "optimal wilderness"

Habitat class	Harvest age	Fraction of forest area harvested in class
	Years	Percent
Seedling	HSE = 0	SEF = 0
Sapling	HSA = 0	SAF = 0
Pole-6	HP6 = 0	P6F = 0
Pole-8	HP8 = 0	P8F = 0
Pole-10	HP1 = 0	P1F = 0
Mature timber	HMT = 0	MTF = 0
Old-growth	HOG = 0	OGF = 0

Initial size of harvested openings, ISO = 0.
Standard deviation of harvested openings, ISD = 0.

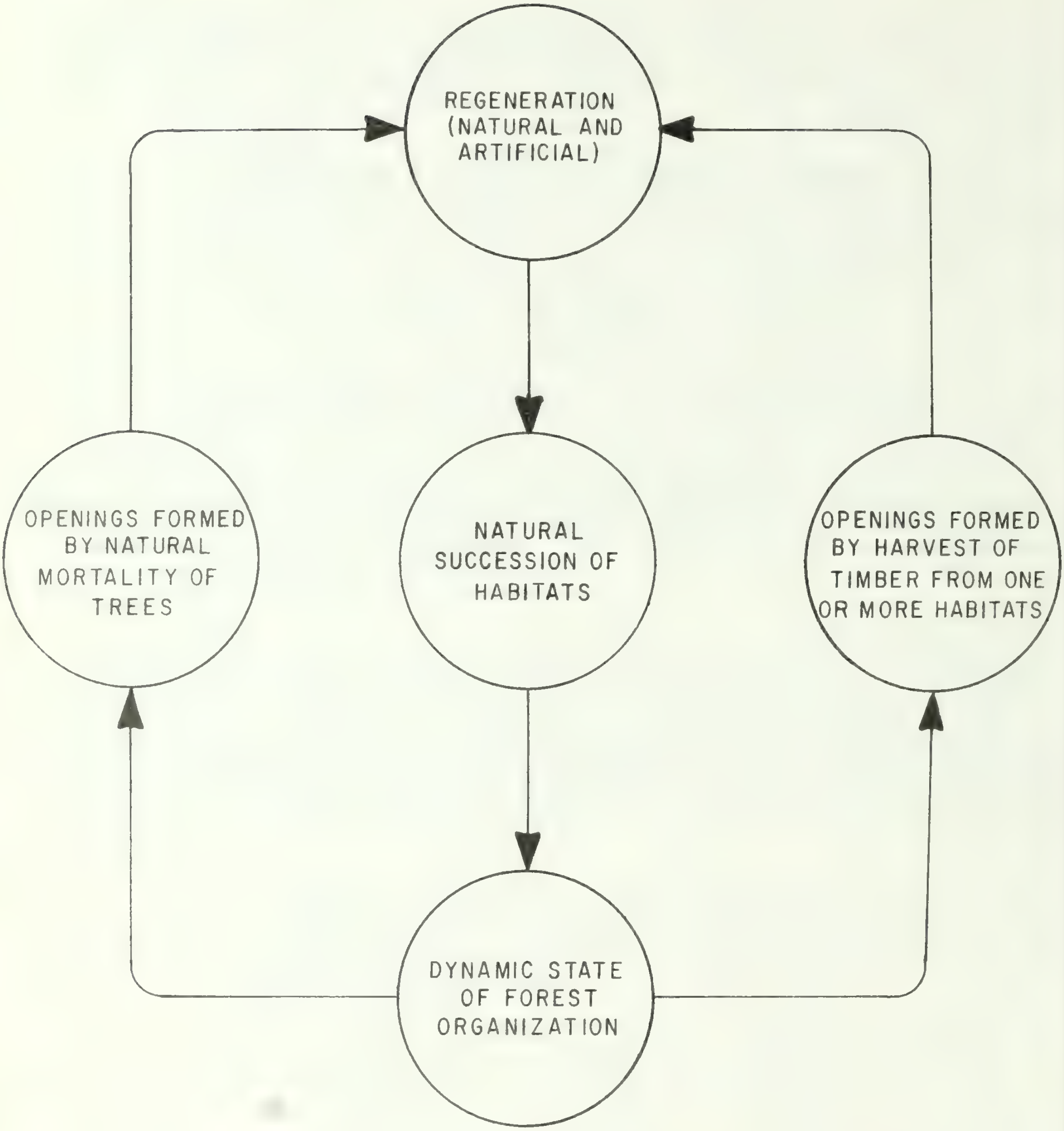
REGENERATION (NATURAL AND ARTIFICIAL)
OPENINGS FORMED BY NATURAL MORTALITY OF TREES
NATURAL SUCCESSION OF HABITATS
OPENINGS FORMED BY HARVEST OF TIMBER FROM ONE OR MORE HABITATS
DYNAMIC STATE OF FOREST ORGANIZATION

Figure 2.--The dynamics of the three DYNAST models.

The manager must adhere to the rates of harvest and sizes of openings in order to implement the mode of management specified by the strategic and tactical plans. Within these constraints, in-place enhancements are implemented by the manager as opportunities arise. Some examples are thinning, pruning, leaving den trees, making waterholes, locating trails, applying fertilizers, and weeding. Such measures are opportunistic, in that they depend upon accessibility, the availability of investment funds, local markets, demands for certain benefits, and the state of the specific forest being considered.

In-place enhancements may or may not make important changes in the states of forest organization. Should in-place enhancements have an important effect on the distribution of habitats and the algorithms that relate benefits to habitats, these effects should become evident in the periodic inventories. For example, if large areas of pole stands are thinned annually for one or more decades, the result could be to speed the transition to mature timber habitats. Such changes, if real and important, should be apparent in the periodic inventories. If such in-place enhancements can be confidently projected through the next inventory period, appropriate adjustments are made in the planning model.

It is evident that periodic inventories are essential for keeping the planning models and the mental models congruent with the real forest.

2.7 Inventories

Inventories are to be repeated at intervals, possibly 10 years. The purpose for inventories is to keep differences among the mental model, the planning model, and the real forest within acceptable limits. One use of repeated inventories is to adjust the analytic silviculture controls. Also, the inventories provide information for evaluating the performance of the management system.

Inventories should be limited to collecting information needed to evaluate and refine the functioning of the core model: the delays for succession, the rotation age for maximum timber production, the model's running estimate of the proportionate distribution of habitats, and the coefficients that define the mode of management.

Since the system is based on the relationship between forest benefits and habitats, a practical classification of habitats must be made for the area under study. The continuum of succession must be divided into classes that are significant for the benefits being considered. The classification will vary for different types of forest and can be modified whenever a new relationship is discovered between a particular age class and a particular benefit. The examples presented in this report use the following classification for the Appalachian hardwood forests:

Seedling habitats.--Stands with half of the dominant and codominant trees less than 1 inch d.b.h. (2.5 cm). A few scattered large trees are admitted.

Sapling habitats.--Stands with half of the dominant and codominant trees between 1 and 5 inches d.b.h. (2.5 to 12.4 cm). A few scattered large trees are admitted.

Pole habitats.--Stands with half of the dominant and codominant trees between 6 and 11 inches d.b.h. (12.5 to 27.7 cm). Pole habitats are classified by 2-inch (5 cm) diameter classes as pole-6, pole-8, and pole-10 habitats.

Mature timber habitats.--Stands with half of the dominant and codominant trees between 11 and 16 inches d.b.h. (27.8 to 40.6 cm).

Old-growth habitats.--Stands with half of the dominant and codominant trees larger than 16 inches d.b.h. (40.7 cm).

3. ILLUSTRATIONS

3.1 Definitions

An area of 6,396 acres of representative Appalachian hardwood forest in the Big Ivy Watershed of Buncombe County, North Carolina, is used to illustrate five modes of management that have been selected for an optimum. This is the same forest area used to model DYNAST-MB (Boyce 1977) and DYNAST-TM (Boyce 1978a). The published structures and performances of these models can be compared directly with the illustrations in this Paper for DYNAST-OB.

Each mode is illustrated by one computer-printed table and three computer-printed plots (table 2; figs. 3, 4, 5). All of the computer-printed illustrations have the same format. The codes for the variables are defined in Appendix C.

The first line at the top of each table or plot identifies the program, DYNAST-OB; the area, Unit 16, Big Ivy, standard lands; the date and time the model was run; and the mode of management.

The second and third lines in the tables name some of the variables; the third and fourth lines indicate the location of decimal points. For example, E + 03 means the number should be multiplied by 10^3. The first column in the tables is time in years. Data are printed annually for the first 10 years, then at 40-year intervals. Any combination of variables can be printed by changing the print cards (Appendix B, Program Controls Sector).

The second line on the plots lists the variables and the symbols used in the plot. The scales for the plots are indicated in the next one or more lines. For example, the plots for the proportional distribution of habitats have two scales. The proportion of seedling habitats is plotted on a scale of 0 to 40 percent. The proportion of saplings, pole-6, pole-8, mature, and old-growth habitats is scaled from 0 to 80 percent. All of the benefit and impact plots are scaled from 0 to 1, where 1 is the theoretical maximum according to the assumptions of the benefit algorithms.

Time, in years, is plotted in the first column of the charts. The variables are plotted annually for the first 10 years and then at 4-year intervals. Time begins at the time of the inventory, and plottings are shown for 170 years. This period is long enough for the faster rates of harvest to bring the distribution of habitats and the indices for benefits to a steady state. Although the wilderness mode continues to oscillate for about 550 years, 170 years of data provide sufficient information for management decisions.

Groups of letters in the last columns on the right-hand side of the charts show coincident indices. The first letter of each group appears on the plot; the other indices are at the same location as the plotted symbol. These groups of symbols must not be confused with indices in the column for value 1 of the plot.

The following illustrations include only the plan selected for providing the optimum. A number of alternative modes of management were examined but only one was selected for the next period of management. The process for selecting a mode of management is described by Boyce (1977, 1978a).

3.2 The "Optimal Wilderness" Mode

A place to begin is to perceive the optimum to be no human intervention into the natural dynamics of the forest. The analytic silviculture controls for all variables are set at 0 (table 1). No harvest is made from any of the habitats, and no opening sizes are specified for harvesting. Openings will occur by natural mortality of trees. Sizes of the openings are determined by the rates of natural mortality (Runkle 1979). This mode of management is designated "optimal wilderness."

The model changes the proportional distribution of habitats over time to simulate the way mortality in the real forest changes the distribution of the habitats (fig. 3). The initial inventory of the forest (at time 0) reveals that relatively small proportions of the forest are in seedling, mature timber, and old-growth habitats; most of the forest is in 6-inch pole, 8-inch pole, and 10-inch pole habitats. The relatively low rates of mortality

Table 2.--Information about the state of the forest, over time, when managed with the optimal wilderness mode. The number of acres, by years, is printed for each habitat: seedlings (SED), saplings (SAP), pole-6 (P6), pole-8 (P8), pole-10 (P1), mature timber (MT), and old growth (OG). The number of acres to be sold from each habitat, by years, is printed below the number of acres in each habitat. Other information listed includes the potential-timber index (PTI), the total volume of timber removed (VT), by years, and the values of some variables such as PSE and PSA that are used in the algorithms. Definitions for these variables are given in Appendix C. Different kinds of information can be printed by changing the print cards.

```
PAGE 6      DYNAST-CB 16 B.IVY ST   11/16/78 21:52   OPTIMUM WILDERNESS

  TIME     SED     SAP      P6      P8          P1      MT      OG     PTI     PSE          PP6    PSEA     P1M     BAL      OPS
           SES     SAS     P6S     P8S         P1S     MTS     OGS      VT     PSA          POG    PO8M     PMC     CPM       WY
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  E+00    E+00    E+00    E+00    E+00        E+00    E+00    E+00    E+00    E-03         E+00    E+00    E+00    E+00     E+00
          E+00    E+00    E+00    E+00        E+00    E+00    E+00    E+00    E+00         E+00    E+00    E+00    E+00     E+00
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    .0  200.00  1254.0  1843.0   740.0      1808.0   366.0   185.0      0.  31.270       .28815  .22733  .33990   .8838       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .19606       .02892  .45560  .08615      0.   215.64
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1.  163.86  1250.8  1763.9   810.7      1768.6   444.7   194.8      0.  25.620       .27579  .22118  .34605   .9514       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .19556       .03046  .47280  .09999      0.   191.71
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    2.  134.48  1241.2  1669.9   872.1      1735.4   519.4   206.7      0.  21.026       .26421  .21509  .35253  1.0200       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .19406       .03232  .48888  .11353      0.   171.79
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    3.  110.61  1226.3  1620.3   924.6      1707.7   590.4   220.6      0.  17.294       .25333  .20902  .35931  1.0898       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .19173       .03449  .50387  .12680      0.   155.13
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    4.   91.24  1207.3  1554.7   969.3      1684.8   658.0   236.5      0.  14.265       .24308  .20302  .36630  1.1608       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .18876       .03697  .51785  .13985      0.   141.14
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    5.   75.55  1185.2  1492.8  1006.8      1665.9   722.7   254.2      0.  11.812       .23339  .19711  .37344  1.2331       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .18530       .03974  .53086  .15272      0.   129.36
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    6.   62.86  1160.7  1434.2  1037.9      1650.3   784.5   273.6      0.   9.826       .22423  .19131  .38068  1.3067       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .18148       .04277  .54296  .16543      0.   119.39
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    7.   52.62  1134.7  1378.5  1063.2      1637.4   843.9   294.6      0.   8.227       .21553  .18563  .38795  1.3814       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .17740       .04607  .55418  .17801      0.   110.92
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    8.   44.40  1107.5  1325.7  1083.3      1626.8   901.0   317.3      0.   6.941       .20727  .18010  .39522  1.4575       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .17316       .04961  .56458  .19047      0.   103.70
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    9.   37.81  1079.6  1275.4  1098.6      1618.0   955.9   341.4      0.   5.912       .19940  .17471  .40243  1.5348       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .16880       .05338  .57419  .20284      0.    97.50
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   10.   32.58  1051.4  1227.4  1109.7      1610.6  1008.9   367.0      0.   5.093       .19190  .16948  .40955  1.6134       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .16439       .05737  .58305  .21511      0.    92.17
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   50.   49.09   417.0   332.0   545.5      1115.1  1968.3  2006.4      0.   7.676       .05190  .07288  .48207  4.5470       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .06520       .31370  .56736  .62144      0.    60.29
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   90.   91.43   446.9   216.9   249.8       514.7  1494.4  3432.5      0.  14.295       .03392  .08417  .31412  2.9907       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .06988       .53657  .35317  .77032      0.    90.07
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  130.  109.15   577.1   266.4   248.7       345.2   938.7  3964.0      0.  17.065       .04165  .10729  .20074  1.6088       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .09023       .61976  .23963  .76652      0.   110.46
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  170.  111.20   643.0   310.8   296.1       369.9   720.6  3996.7      0.  17.385       .04859  .11791  .17050  1.7020       0.
            0.      0.      0.      0.          0.      0.      0.      0.  .10053       .62487  .21679  .73753      0.   116.24
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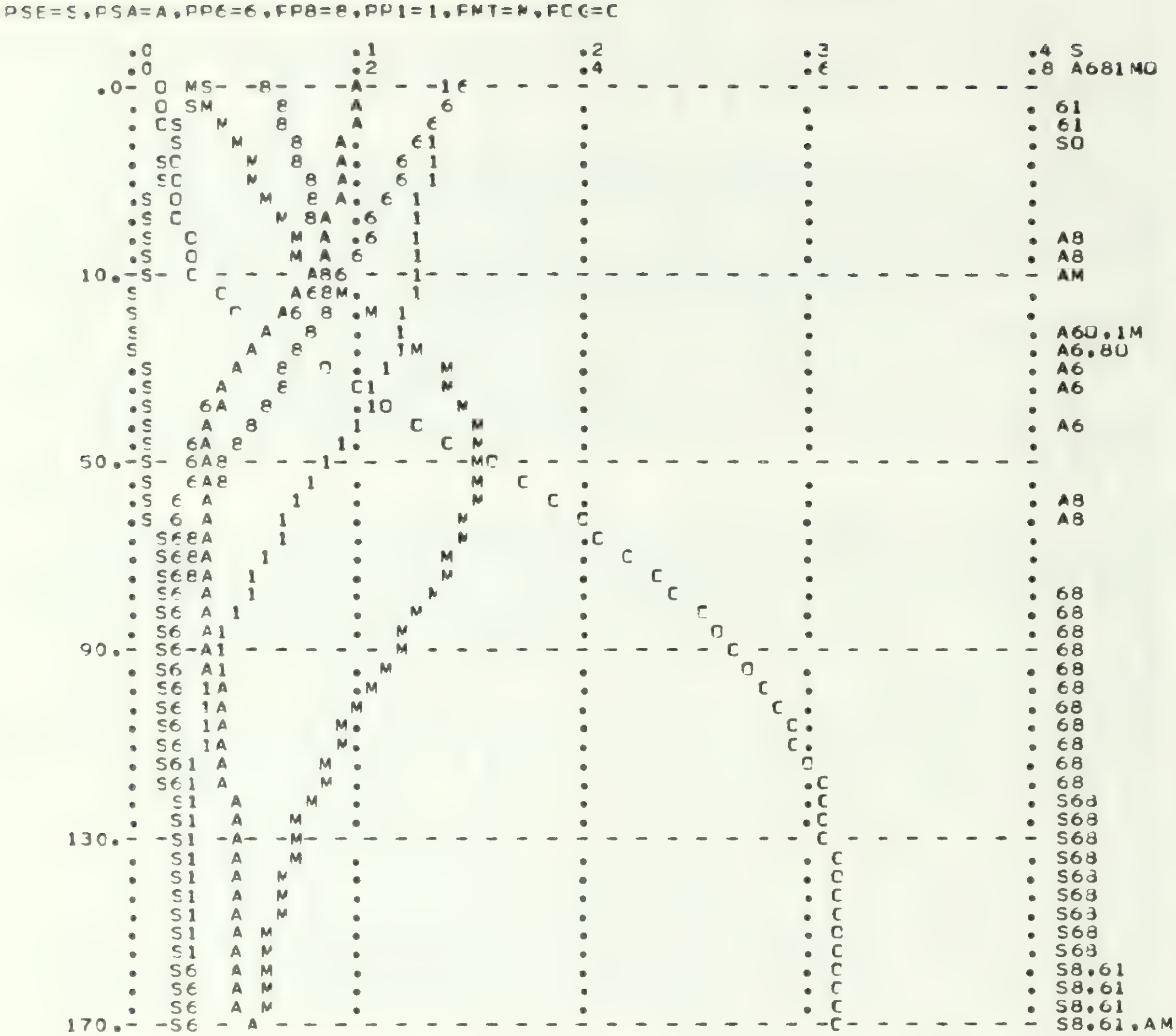

Figure 3.--The proportional distribution of seedlings (S), saplings (A), pole-6 (6), pole-8 (8), pole-10 (1), mature timber (M), and old-growth (O) habitats for the optimal wilderness mode of management.

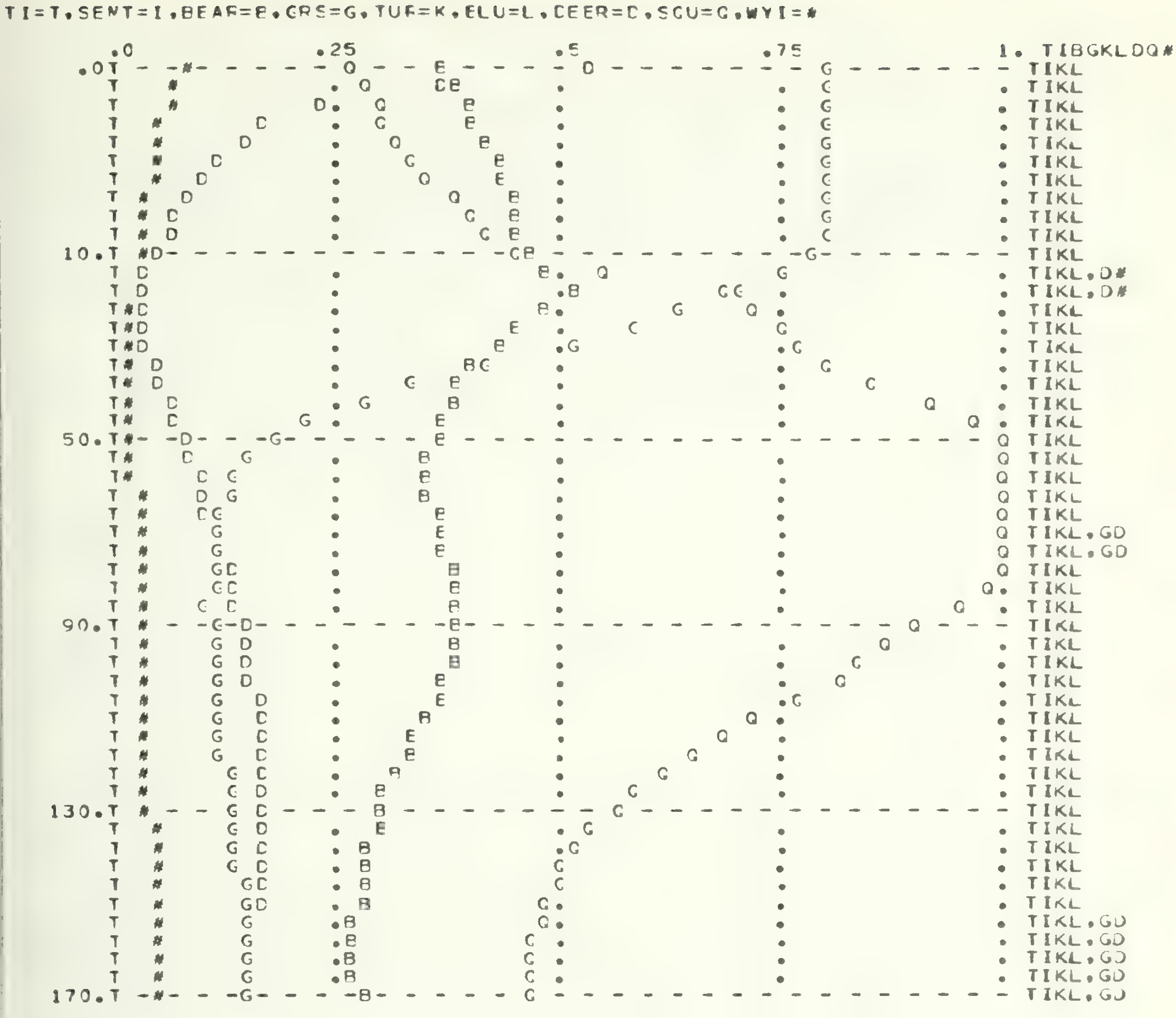

Figure 4.--The relative production of timber (T), sediment (I), and water (WYI), and the relative livelihood for black bear (B), grouse (G), turkey (K), bluebirds (L), deer (D), and squirrels (Q) for the optimal wilderness mode of management.

```
VIS=V,UGL=U,OVN=C,PIL=P,FLIC=F ,DCN=N,TWE=W,PWE=E,HAR=H,CC=*

    .0            .25             .5            .75            1.  VUOPFNWE
  .0UF- W - H*-P- - - - - - -V- - - - - - - - - - - - - - - N -O- PE
    UF W    *H PE  .      V       .              .           O  . ON
    LF W    * H P E.   V          .              .          ON  .
    UF W   *   HP VE              .              .        C   N .
    UF W   *  VH P . E            .              .       O    N .
    LF W   V    HP .  E           .              .      O     N . V*
    U  W V *      PH    E         .              .     C       N. UF
    L  W V *      P. H   E        .              .    C        N. UF
    U  W V*        P   H   E      .              .   C          N UF
    U  W V*        .P     H  E    .              .  C           N UF
 10.L -WV * - - - - P - - - H -E- - - - - - - - - -O- - - - - - N UF
    U WV  *        .    F         . H  E        C.              N UF
    U WV  *        .       P      .        C H E .              N UF
    U W V *        .          F   .  C           E   H          N UF
    UW  V *        .           C P.              .  E     H     N UF
    UW  V  *       .       O      .  P           .     E     H  N UF
    LW  V  *       .    C         .     P        .       E     HN UF
    UW  V   *      . C            .        P     .         E    N UF,NH
    UW   V   *     C              .            P .          E   N UF,NH
    UW   V   *    C.              .              .F          E  N UF,NH
 50.UW- -V- - * O - - - - - - - - - - - - - - - - - -P- - - - E N UF,NH
    LW   V     *C  .              .              .    F       E N UF,NH
    LW  V      C*  .              .              .      P      EN UF,NH
    LW  V      O * .              .              .        P     N UF,NEH
    LW   V     C  *.              .              .         P    N UF,NEH
    UF   V    C    *              .              .         P    N FW,NEH
    UF    V   C    *              .              .          P  NE FW,EH
    UF    V   C    .*             .              .           PN E FW,EH
    UF    V   C    . *            .              .           P  E PN,FW,EH
    UF    V   C    . *            .              .          N P E FW,EH
 90.UF- - V - C - - - * - - - - - - - - - - - - - - - - - -N- P E FW,EH
    UF     V  C    .  *           .              .        N    PE FW,EH
    UF     V  C    .   *          .              .      N      PE FW,EH
    UF     V  C    .   *          .              .    N        PE FW,EH
    UF     V  C    .    *         .              .   N          P FW,PEH
    LF     V  C    .    *         .              . N            P FW,PEH
    UF     V   O   .    *         .             N.              P FW,PEH
    UF      V  C   .    *         .           N  .              P FW,PEH
    LF       V C   .    *         .         N    .              P FW,PEH
    UF        VO   .    *         .       N      .              P FW,PEH
130.UF- - - - VO- - - - -*- - - - - - - N - - - - - - - - - - - P FW,PEH
    UF         V   .     *        .    N         .              P VO,FW,PEH
    UF         V   .     *        .  N           .              P VO,FW,PEH
    LF         OV  .     *        . N            .              P FW,PEH
    LF         OV  .     *        . N            .              P FW,PEH
    LF         O V .    *         .N             .              P FW,PEH
    LF          CV .    *         N              .              P FW,PEH
    UF          OV .    *         N              .              P FW,PEH
    UF          OV .    *        N.              .              P FW,PEH
    LF          CV .    *        N.              .              P FW,PEH
170.UF- - - - - OV- - - * - - - -N- - - - - - - - - - - - - - - P FW,PEH
```

Figure 5.--The relative desirability of ugliness (U) and visual appeal (V); the relative constraint of one or more habitats (*); and the relative livelihood for the ovenbird group of birds (O), pileated woodpecker (P), yellow-shafted flicker woodpecker (F), downy woodpecker (N), the towhee group of birds (W), the peewee group of birds (E), and hairy woodpecker (H).

in these young pole stands result in the proportion of area in seedling habitat rapidly declining. After about 10 years, the proportion of area in seedling habitat is near 0. As the proportion of area in old-growth habitats increases and the mortality of dominant trees increases, the proportion of seedling habitats increases to about 1.7 percent after 130 years.

After 10 years, the proportion of old-growth stands increases rapidly and after 130 years approaches a steady state at about 62 percent of the total area. During this same period, successive changes in the various stand-condition classes result in a net increase in the proportion of area in mature timber and a net decrease in the proportion of area in saplings, 6-inch pole stands, 8-inch pole stands, and 10-inch pole stands. These successive changes in the distribution of habitats result in different combinations of benefits being available at different times.

Since no harvest of timber is permitted in the wilderness mode, the potential timber index (T) is 0 for the entire period (fig. 4). Also, no roads are constructed and the sediment index (I) is at the background level of a few hundred pounds per acre per year. The relative increase in sediment is computed by the model to be 0.

The index for turkey habitat is 0 because the absence of harvested openings limits the availability of protein in the form of insects. Also, very small openings provide little opportunity for turkey poults to dry their wings. The lack of openings for feeding and nesting bluebirds results in the potential habitat for bluebird (L) also being 0.

The potential livelihood for squirrels (Q) increases for the first 50 years, remains at the maximum level until the 80th year, then declines to about 48 percent of the potential after 170 years. These changes are related to the change in proportional distribution of habitats (fig. 3), which influences the livelihood for squirrels. We can examine how these changes affect the livelihood for squirrels and other animals (figs. 4, 5) by examining the algorithms that relate the state of organization of the forest to the livelihood for animals.

By printing the values used in the algorithms described by Boyce (1977, 1978a), we can examine how the distribution of habitats, over time, influences the potential livelihood for squirrels (table 2). The proportion of hard-mast-producing habitats (PO8M) exceeds 40 percent of the total area for the first 80 years and does not limit the potential livelihood for squirrels for this time. However, the livelihood for squirrels is limited by a shortage of den trees, because of the relatively small proportion of old growth (POG) for the first 50 years. After 50 years, the proportion of old growth has reached 30 percent, while the proportion of mast-producing habitats continues to exceed 40 percent. The habitat potential for squirrels is maximum. This condition prevails until about year 80, when the proportion of primary hard-mast-producing habitats declines to less than 40 percent. The continued decline in these hard-mast-producing habitats (PO8M) reduces the potential livelihood of squirrels to about 48 percent after 170 years. Old-growth stands are not included in the hard-mast-producing habitats because the production of hard mast by old-growth stands declines with age of the trees.

Similarly, algorithms for expressing the potential livelihood for plants and animals, for sediment, timber yields, cost of management, or other items of interest can be developed. They are then linked in the computer model with the organization of the forest, and the changing consequences displayed over time. The particular combination of algorithms used depends on the availability of information from research and experience (Boyce 1977, 1978a). As new information becomes available, the algorithms are adjusted or new combinations are developed. Adjustments for one algorithm do not require any program changes in the core model nor any adjustments in the other algorithms (sec. 4.5).

In the present example, changes in the potential livelihood for grouse (G), black bear (B), deer (D), and other benefits can be followed in the same way as described for squirrels. The relationships used in the algorithms are described in other places (Boyce 1977, 1978a).

A water-yield index (WYI), recently described by Lloyd Swift (Southeastern Forest Experiment Station, personal communication), expresses the relative changes in streamflow with different modes of management. Streamflow increases with the proportion of total area in seedling and sapling habitats. Thus, the water-yield index (#) declines as the proportion of seedlings and saplings declines during the first 60 years. As the proportion of old growth increases after 60 years and mortality of the dominant trees increases to produce more seedling habitat, the water-yield index increases, but only to a relatively small proportion of the maximum potential (fig. 4).

Another algorithm measures the extent to which certain habitats are constrained by an increase in one or more habitats because of the mode of management. This relationship, called constraint quantum (CQ), is displayed by an asterisk (*) (fig. 5). The logic and the computation of the constraint quantum is described by Boyce and Cost (1978) and by Boyce (1978b). The equations are listed and the variables are defined in Appendixes B and C.

The constraint quantum (*) is 0 when the habitats are equally distributed and the value is 1 when there is only one habitat. For the optimal wilderness mode, the constraint quantum remains below 0.2 until after 50 years (fig. 5). During this period, 0 to 50 years, the distribution of habitats is not greatly constrained (fig. 3), although the proportion of seedling habitat approaches 0 for a short period of time. The greatest constraint occurs after year 50, when the proportion of old-growth stands increases to approximately 62 percent of the total area. Then, the younger classes are constrained to relatively small proportions of the total area (fig. 3). This constraint is indicated by an increase in the CQ value to about 0.34 (fig. 5).

The usefulness of the constraint quantum lies in its indication of the relative constraint of habitats and its indication of possible limits for the livelihood of one or more plants and animals (Boyce and Cost 1978). We cannot know all of the organisms present in a forest. We can develop and use in a planning model a relatively few algorithms that represent a wide variety of life forms. If a livelihood is provided for this variety of life forms, it is likely that a livelihood is provided for most endemic species, if not all. The constraint quantum is a way to indicate potential constraint in the livelihood for some endemi organisms, perhaps including some whose requirements are not included in the other algorithms. However, before this measure of habitat constraint is widely used, more information is needed about how constraining the distribution of certain habitats limits the livelihood of certain life forms.

The wilderness mode indicates a change in the livelihood for a number of animals when certain habitats are constrained. The lack of large openings for the ground-feeding flicker woodpecker limits the potential livelihood of this bird to almost 0. As the proportion of 6-inch pole stands is constrained, the potential livelihood for the ovenbird group of birds declines. The potential livelihood for downy woodpecker declines as the proportion of area in 10-inch poles and mature timber declines. On the other hand, as the area in old-growth stands increases, the potential livelihood for the peewee group of birds, the hairy woodpecker, and the pileated woodpecker increases to a maximum.

3.3 An Optimal Combination of Benefits

It is possible to choose an optimal combination of multiple benefits without preferring any one benefit over another. This ideal is implied in the Multiple Benefit Sustained Yield Act and in the National Forest Management Act of 1978 (16 U.S.C., 528-531). The optimal combination is to have all desirable benefits clustered near some relatively high value that is biologically possible and all undesirable benefits at a low level.

During the development of DYNAST-MB, it was found that a large variety of benefits could be maximized only through the use of two superimposed rotation periods (Boyce 1977). Superimposed rotation periods means that a stand may pass through the mature timber habitat and be harvested at a specified rotation age between 90 and 120 years; then, the next stand on the same area may pass to the age of old-growth habitat and be harvested at a specified rotation age between 121 and 300 years. A certain proportion of the total area is permitted to pass through the old-growth habitat, and the remaining proportion is harvested as mature timber. Such a combination of superimposed rotation periods provides for a wide distribution and dispersion of habitats in the forest, thus favoring a large number of benefits simultaneously.

If the forest had not been previously analyzed, it would be necessary to examine a number of modes of management. However, from the moderate mode of management described for this particular forest in DYNAST-MB (Boyce 1977) we can approximate the analytic silviculture controls that will provide us with an optimal combination. We can harvest mature timber at 100 years with 70 percent of the area rotating through this habitat, and we can harvest old-growth habitats at 200 years with 30 percent of the area rotating through this habitat. We can set the initial size of openings (ISO) at 10 acres with a standard deviation (ISD) of 1 acre (table 3).

Table 3.--The analytic silviculture controls for the mode of management designated "optimal combination"

Habitat class	Harvest age	Fraction of forest area harvested in class
	Years	Percent
Mature timber	HMT = 100	MTF = 70
Old-growth	HOG = 200	OGF = 30

Initial size of harvested openings, ISO = 10.
Standard deviation of harvested openings, ISD = 1.

We keep the wilderness mode in the model as the first run and designate all other modes as reruns. The first set of reruns will be used to refine the control constants for an optimal combination of multiple benefits. We change only the control constants given in table 3 when the mode for optimal combination is run. Several different reruns may be made, each with different values for the control constants. The set of control constants found to provide a combination of benefits that most nearly approaches our perception of an optimal combination is selected from the various trial runs. For this illustration, our choice of a management mode was the same as the first approximation for the analytic silviculture controls (table 3).

The rates of harvest of mature timber and old growth required during the first 10-year planning period are printed (table 4). During the first 10 years, no old-growth timber (OGS) is harvested, since there is a deficiency of old growth in the original inventory (fig. 6). Old-growth timber is not harvested until after about 30 years. When the stands are brought to the desired state of organization, after about 130 years, the rate of harvest of old-growth timber is about 9½ acres per year.

The harvest from the mature timber stands increases from about 12 acres per year at the present to about 45 acres per year in the 10th year. When the distribution of habitats is brought to the desired goal, the harvest of mature timber (MTS) remains about 45 acres per year (table 4).

The subjective choice of an optimal combination is based on the distribution of benefits. In this example, all of the first group of benefits considered, except water, are clustered between 60 and 80 percent of the maximum potential (fig. 7). The second group of benefits considered (fig. 8) clusters between 48 and 80 percent of the maximum potential. The index for ugliness (U) is relatively low. The constraint quantum declines during the first 30 years to about 0.1 (fig. 8) and, as indicated by the distribution (fig. 6), none of the habitats are highly constrained. We can assume that large numbers of plants and animals, for which we have no algorithms, have combinations of habitats for a reasonable livelihood.

3.4 Optimal Livelihood for Deer

Another optimum that might be chosen is to bring the forest to a state of organization that will maximize the livelihood for deer. According to the algorithms for deer (Boyce 1977), an optimal livelihood exists when 7 percent or more of the area is in seedling habitats for browse, the opening sizes are less than 3 acres, and 20 percent or more of the total area is in pole-10 and mature timber habitats for the production of hard mast. For different forests, research and experience may change these algorithms. For example, experience may show that the proportion of total area in seedling habitat does not need to be as high as 7 percent. In another forest, there may be little need for habitats that produce hard mast. The algorithms can be easily changed (Boyce 1977). For each particular forest, it is important that the algorithms express the best available knowledge about the livelihood of plants and animals in relation to the state of organization of the forest.

There are possibly a number of different combinations of harvest rates and opening sizes that would bring the deer-habitat index (D) to the maximum level of 1. One could mathematically determine all these possible combinations and then select one as the set of control constants. Since the cost of reruns is relatively small, it is easy to make a good guess and then make several reruns until one finds an acceptable set of control constants for the optimal livelihood for deer.

Table 4.--Information about the state of the forest, over time, when managed with the optimal combination mode

TIME	SED SES	SAP SAS	F6 P6S	F8 P8S	FI PIS	WT NTS	CG OGS	PTI VT	PSE PSA	PP6 FOG	PSEA PD8M	PIW PMO	BAL OPM	OPS WY
E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+03	E-03 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	200.00 0.	1254.0 0.	1843.0 0.	740.0 0.	1808.0 0.	378.4 12.351	185.00 .0000	.08545 27.55	31.270 .19606	.28815 .02892	.22733 .45753	.34183 .08808	.8876 .10006	6.176 215.64
1.	169.24 0.	1251.0 0.	1763.9 0.	810.7 0.	1768.6 0.	460.9 20.343	185.00 .0000	.12395 39.96	26.460 .19559	.27579 .02892	.22205 .47533	.34857 .10098	.9548 .10006	8.958 195.25
2.	147.96 0.	1242.7 0.	1689.9 0.	872.1 0.	1735.4 0.	537.0 27.481	185.00 .0000	.19596 63.17	23.133 .19429	.26421 .02892	.21742 .49162	.35528 .11288	1.0208 .15892	8.917 180.73
3.	135.79 0.	1230.6 0.	1620.3 0.	924.6 0.	1707.7 0.	605.7 35.482	185.00 .0000	.28056 90.44	21.230 .19241	.25334 .02892	.21364 .50626	.36170 .12362	1.0841 .19556	10.375 171.94
4.	131.85 0.	1216.8 0.	1554.9 0.	969.3 0.	1684.8 0.	666.4 42.216	185.00 .0000	.37424 120.64	20.614 .19025	.24311 .02892	.21086 .51916	.36761 .13312	1.1436 .29023	9.325 168.42
5.	134.92 0.	1202.9 0.	1493.3 0.	1006.9 0.	1665.9 0.	719.2 44.772	185.02 .0000	.46598 150.21	21.095 .18807	.23348 .02893	.20916 .53032	.37290 .14137	1.1981 .33883	9.945 169.50
6.	142.98 0.	1190.1 0.	1435.3 0.	1038.0 0.	1650.3 0.	764.6 44.772	185.79 .0000	.52951 170.69	22.354 .18607	.22441 .02905	.20843 .53985	.37756 .14859	1.2473 .40799	9.385 173.93
7.	153.03 0.	1179.4 0.	1380.6 0.	1063.4 0.	1637.4 0.	804.9 44.772	187.62 .0000	.56675 182.70	23.926 .18440	.21586 .02933	.20833 .54811	.38185 .15518	1.2921 .42867	9.561 179.80
8.	163.27 0.	1171.1 0.	1329.2 0.	1083.5 0.	1626.8 0.	841.6 44.772	190.46 .0000	.58858 189.73	25.526 .18310	.20781 .02978	.20862 .55534	.38593 .16136	1.3336 .48293	8.814 185.96
9.	172.81 0.	1165.0 0.	1260.8 0.	1099.1 0.	1618.0 0.	875.7 44.772	194.27 .0000	.60137 193.86	27.018 .18215	.20025 .03037	.20917 .56173	.38989 .16728	1.3720 .40679	10.691 191.81
10.	181.28 0.	1161.0 0.	1235.4 0.	1110.5 0.	1610.7 0.	907.8 44.772	199.00 .0000	.60887 196.28	28.343 .18152	.19315 .03111	.20987 .56738	.39375 .17304	1.4078 .39249	11.219 197.09
50.	254.63 0.	1333.2 0.	673.8 0.	763.1 0.	1248.3 0.	1414.7 44.772	726.64 8.4074	.74082 238.81	39.811 .20844	.10534 .11361	.24825 .53566	.41635 .33479	1.5149 .57154	9.239 256.81
90.	277.20 0.	1558.9 0.	745.6 0.	720.5 0.	990.3 0.	1138.3 44.772	584.34 9.5940	.77040 248.34	43.340 .24373	.11657 .15390	.28707 .44545	.33280 .33187	1.1036 .52967	10.281 286.81
130.	276.29 0.	1635.6 0.	805.6 0.	786.7 0.	1016.3 0.	970.5 44.772	922.28 9.5940	.77040 248.34	43.197 .25572	.12595 .14420	.29892 .43364	.31064 .29593	1.0206 .49740	10.978 291.38
170.	273.02 0.	1643.0 0.	820.5 0.	816.0 0.	1069.9 0.	981.9 44.772	807.64 9.5940	.77040 248.34	42.687 .25688	.12829 .12627	.29956 .44837	.32079 .27979	1.0479 .53931	10.092 289.73

```
PSE=S.PSA=A.PP6=6.PP8=8.PP1=1.FMT=M.FCG=C

        .0               .1                .2               .3                .4 S
        .0               .2                .4               .6                .8 A681MO
      .0- O MS-   -8- - -A- - -16 - - - - - - - - - - - - - - - - - - - - - - -
        . O SM     8     A      6          .                .                 . 61
        . CS   M   8     A     6           .                .                 . 61
        . CS    M    8  A.    61           .                .                 .
        . CS     M   8  A.   6 1           .                .                 .
        . OS     M    8 A.   6 1           .                .                 .
        . CS      M   8 A.  6 1            .                .                 .
        . C  S    M   8 A.6   1            .                .                 .
        . O  S     M   8A.6   1            .                .                 .
        . C  S     M   8A6    1            .                .                 .
     10.- O  S - - -M-8A - -1- - - - - - - - - - - - - - - - - - - - - - - - - -  A6
        .  C  S       M6A.    1            .                .                 . 68
        .  C  S      6 8A.   1             .                .                 . 8M
        .    CS    6  8 A.   1             .                .                 . AM
        .    CS   6   8 AM   1             .                .                 .
        .     S   6 8   A.M1               .                .                 . SO
        .     SO  6 8    AM1               .                .                 .
        .      SO6 8     A1                .                .                 . 1M
        .      SC6 8     A1M               .                .                 .
        .      S 68      A M               .                .                 . A1,6O
     50.- - - S 68- - -1AM- - - - - - - - - - - - - - - - - - - - - - - - - -  8O
        .      S 68     1.A                .                .                 . AM,8O
        .      S 68C    1.A                .                .                 . AM
        .      S 6 C   1 .MA               .                .                 . 68
        .      S 6 C   1 .MA               .                .                 . 68
        .      S 6  C 1  M A               .                .                 . 68
        .      S 6  C1   M A               .                .                 . 68
        .      S 6  O1  M.   A             .                .                 . 68
        .      S 86 C1  M.   A             .                .                 .
        .      S 86 O1  M.   A             .                .                 .
     90.- - - -S86-  1M- -   A - - - - - - - - - - - - - - - - - - - - - - - -  1O
        .       S 6  1M  .   A             .                .                 . 68,1O
        .       S 6  1M  .    A            .                .                 . 68,1O
        .       S 6  1   .    A            .                .                 . 68,1MO
        .       S 6  1   .    A            .                .                 . 68,1MO
        .       S 6 O1   .    A            .                .                 . 68,1M
        .       S 6 C1   .    A            .                .                 . 68,1M
        .      S  6 O1   .    A            .                .                 . 68,1M
        .      S  6 C1   .    A            .                .                 . 68,1M
        .      S  6 M1   .    A            .                .                 . 68,MO
    130.- - - S -6-M1 - -   -A- - - - - - - - - - - - - - - - - - - - - - - -  68,MO
        .      S  6 M1   .    A            .                .                 . 68,MO
        .      S   86M1  .    A            .                .                 . MO
        .      S   86M1  .    A            .                .                 . 6O
        .      S   86M1  .    A            .                .                 . 6O
        .      S   86M1  .    A            .                .                 . 6O
        .      S   86M1  .    A            .                .                 . 6O
        .      S    6M1  .    A            .                .                 . 68O
        .      S    6M1  .    A            .                .                 . 68O
        .      S   6M 1  .    A            .                .                 . 68O
    170.- - - S -C6 M1- -   -A- - - - - - - - - - - - - - - - - - - - - - - -  68
```

Figure 6.--The proportional distribution of habitats for the optimal combination mode of management.

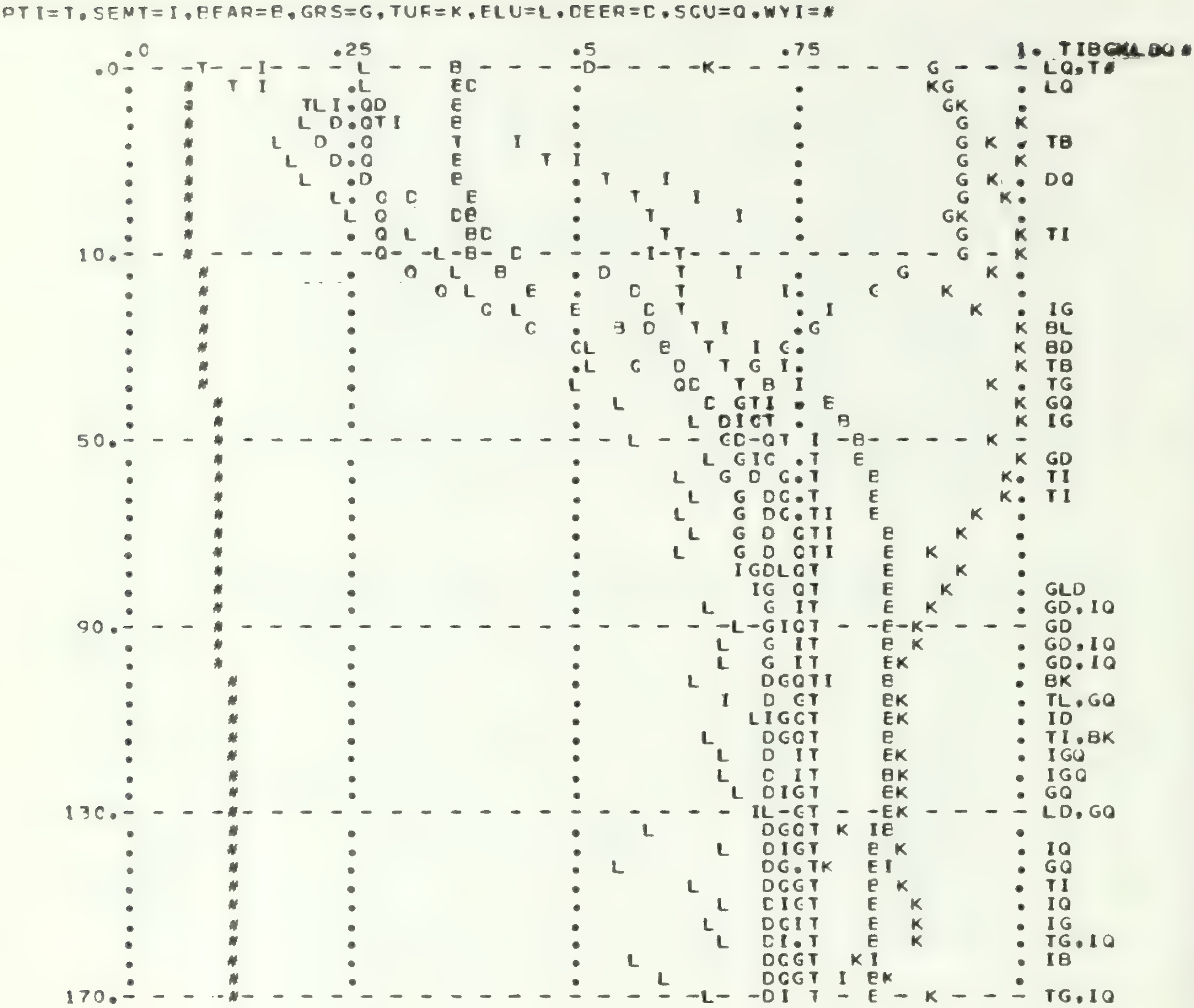

Figure 7.--The relative production, availability, or desirability of a group of benefits for the optimal combination mode of management.

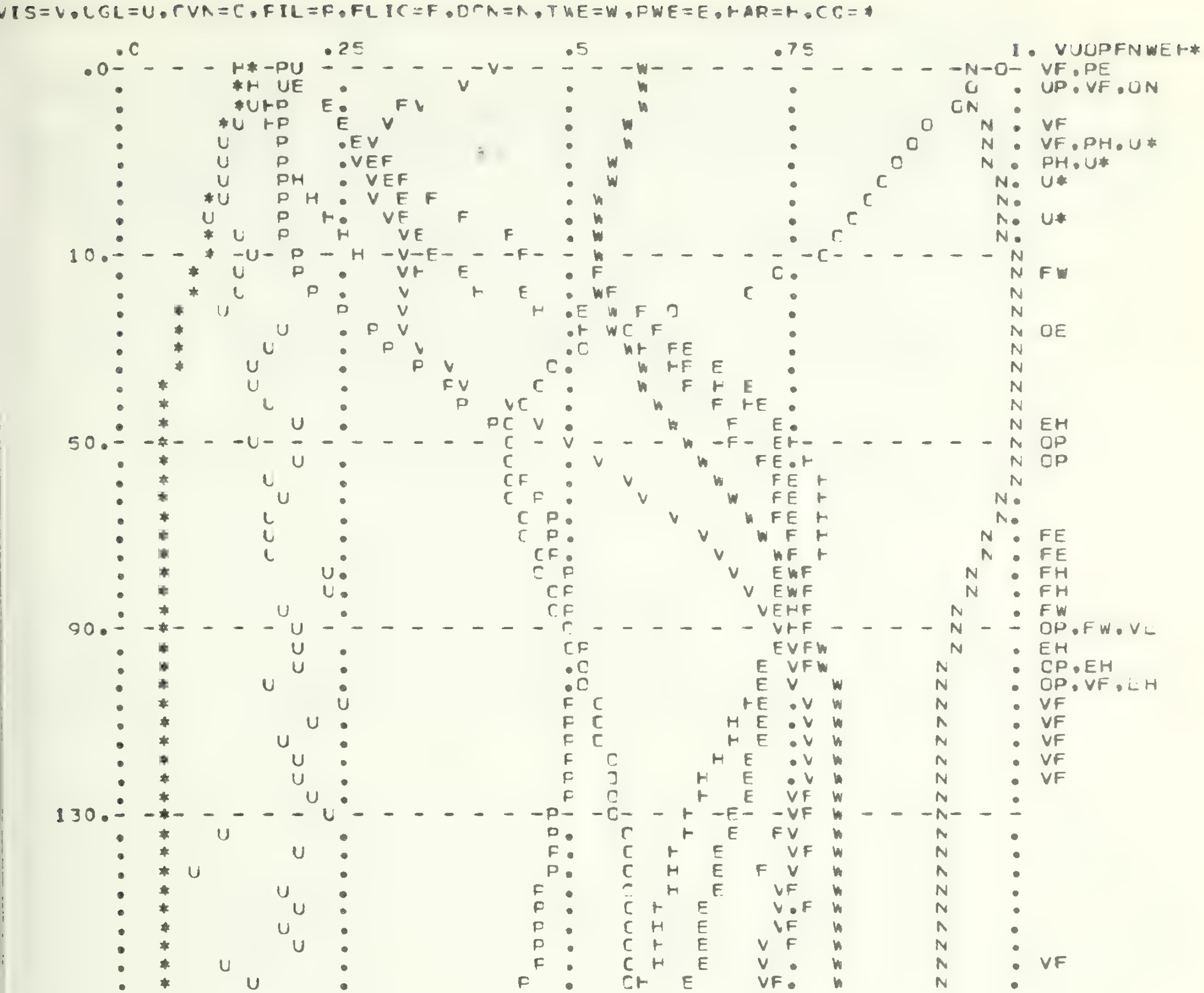

Figure 8.--The relative production, availability, or desirability of a group of benefits for the optimal combination mode of management.

Actually, one programs the DYNAST-OB model to make several reruns in which the analytic silviculture controls are varied in some logical pattern. After we examine the several reruns, we select one that approaches the optimal livelihood for deer (table 5). Our choice provides a large amount of browse by harvesting 35 percent of the area as saplings at age 30; hard mast is provided by letting the rest of the area grow to mature timber harvested at 100 years of age.

Table 5.--The analytic silviculture controls for the mode of management designated "optimal deer"

Habitat class	Harvest age	Fraction of forest area harvested in class
	Years	Percent
Sapling	HSA = 30	SAF = 35
Mature timber	HMT = 100	MTF = 65

Initial size of harvested openings, ISO = 3.
Standard deviation of harvested openings, ISD = 0.5.

The rate of harvest from the sapling habitat increases from 18 acres per year to 51 acres per year during the first 10 years (table 6). When the distribution of habitats is brought to the desired state of organization, the rate of harvest from sapling habitats is about 74 acres per year. The rate of harvest from the mature timber habitat is about 41 acres per year. The proportion of area in seedling habitat is about 9 percent, and the proportion of area in 10-inch poles and mature timber is about 23 percent. Saplings make up the largest proportion of the total area (fig. 9).

The consequences of providing an optimal livelihood for deer are many (figs. 10, 11). For example, the potential livelihoods for squirrel, black bear, turkey, bluebird, pileated woodpecker, hairy woodpecker, and peewee-type birds are reduced to a low level. Sediment is at the maximum because of the high rate of harvest with small-diameter openings and the requirement to build many miles of roads and trails to get to these openings. The sediment movement could be reduced if one chose to fell the trees in the mature timber and sapling habitats without building roads to remove the felled trees. Old-growth habitat is virtually eliminated. This constraint is indicated by the constraint quantum values, which increased to almost 0.25 (fig. 11).

The potential-timber index exceeds the maximum between the 10th and 50th year. During this period, the old growth and some of the mature timber in the original inventory is being liquidated. When the distribution of habitats is at the desired state of organization, the potential-timber index is approximately 0.95. This includes the wood harvested in the sapling habitats. The production of sawtimber is thus considerably below the maximum.

3.5 Optimal Livelihood for Squirrel and Bear

Here the perceived optimum is a state of forest organization that provides the optimal livelihood for black bear and squirrel. For the sample forest in the Southern Appalachians, the algorithms for these two animals are closely related. For example, the availability of dens for both bear and squirrel are assumed to be at maximum when the total area is in 30 percent old-growth habitats. Also, the availability of hard mast for both animals is assumed to be at maximum whenever the proportion of total area in 8-inch poles, 10-inch poles, mature timber, and old-growth habitat exceeds 40 percent. Bears additionally require soft mast, such as blackberries, huckleberries, gooseberries, grapes, and sassafras berries, during the summer and early fall before hard mast becomes available. This requirement is satisfied by having at least 20 percent of the total area in seedling and sapling habitat. The size of the openings formed by harvest apparently is not critical for either animal so long as the openings are large enough for plants that produce soft mast to invade and survive for a few years. To provide these fruits, the initial size of openings (ISO) is set at 13 acres and the initial standard deviation (ISD) at 1 acre (table 7). A secondary consideration is that 13-acre openings do not arbitrarily discriminate against the potential livelihood for deer, turkey, grouse, and certain songbirds that feed on plants temporarily occupying the openings.

Table 6.--Information about the state of the forest, over time, when managed with the optimal deer mode

```
  TIME     SED     SAP      F6      F8          F1      MT      OG     PTI     PSE         PP6    PSEA    P1M     BAL     OPS
           SES     SAS     P6S     F8S         P1S     MTS     OGS      VT     PSA         POG    PC8M    PMO     OPM      WY
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  E+00    E+00    E+00    E+00    E+00        E+C0    E+CC    E+00    E+00    E-03        E+00    E+00    E+00    E+00    E+00
          E+00    E+00    E+C0    E+C0        E+00    E+00    E+00    E+03    E+00        E-03    E+00    E+00    E+00    E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    .0  200.00  1254.0  1843.0   740.0      1808.0   366.0  301.19   .8625  31.270      .28815  .22733  .33990   .8838  3.2311
            C.    .00C      C.      0.          0.    .000  116.19  278.02  .19606      47.091  .45560  .10431  1.7992  215.64
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1.  222.75  1294.7  1723.2   810.2      1768.6   456.0  232.30  1.1471  34.826      .26941  .23725  .34781   .9365  3.6920
            C.  18.988      C.      C.          0.  18.988   72.77  369.79  .20242      36.319  .47449  .10762  2.0943  233.30
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    2.  257.76  1336.0  1611.1   868.6      1735.3   540.3  155.54  1.1918  40.301      .25190  .24919  .35578   .9810  2.4587
            0.  37.173      0.      0.          0.  32.467   22.85  384.19  .20889      24.318  .49159  .10879  3.6061  259.05
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    3.  293.20  1371.8  1506.4   916.0      1707.4   611.9   97.25  1.1073  45.841      .23552  .26031  .36262  1.0202  3.1875
            0.  38.110      0.      0.          C.  39.792    7.18  356.94  .21447      15.206  .50584  .11088  2.8113  284.70
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    4.  321.20  1405.6  1408.4   953.5      1683.9   672.4   58.99   .9849  50.218      .22021  .26999  .36840  1.0557  2.6625
            0.  39.409      0.      0.          0.  41.574    2.33  317.49  .21977       9.223  .51748  .11435  3.2943  305.35
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    5.  342.23  1439.3  1316.9   962.3      1663.9   723.6   36.22   .9178  53.506      .20589  .27853  .37327  1.0876  2.9727
            0.  40.960      0.      0.          0.  41.574    1.52  295.86  .22503       5.663  .52686  .11879  2.8910  321.41
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    6.  358.09  1473.1  1231.2  1003.3      1646.7   768.5   23.79   .8613  55.986      .19250  .28629  .37761  1.1163  2.6927
            0.  42.663      0.      0.          0.  41.574    2.06  277.66  .23031       3.720  .53448  .12387  3.1688  334.09
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    7.  370.91  1506.9  1151.2  1017.5      1631.7   809.0   17.73   .8445  57.990      .17999  .29360  .38159  1.1417  2.7805
            0.  44.452      0.      0.          0.  41.574    2.98  272.24  .23560       2.772  .54067  .12925  3.0906  344.78
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    8.  382.26  1540.8  1076.3  1025.5      1618.3   846.3   15.44   .8281  59.766      .16828  .30067  .38533  1.1636  2.4069
            C.  46.777      C.      C.          0.  41.574    3.98  266.96  .24091       2.413  .54567  .13473  3.6334  354.51
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    9.  393.21  1574.6  1006.4  1028.2      1606.0   881.1   15.33   .8597  61.478      .15734  .30767  .38885  1.1819  3.3454
            0.  49.197      C.      C.          0.  41.574    4.98  277.13  .24619       2.397  .54961  .14016  2.6822  363.97
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   10.  404.44  1608.2   940.9  1026.3      1594.4   913.9   16.46   .8766  63.233      .14711  .31468  .39217  1.1967  3.6093
            0.  51.599      C.      C.          C.  41.574    5.94  282.57  .25144       2.574  .55262  .14546  2.5622  373.60
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   50.  581.08  2011.6   409.9   419.4       866.0  1173.1   45.81  1.0912  90.850      .06408  .56171  .31881   .6142  2.7510
            0.  59.676      C.      0.          C.  41.574   14.86  351.77  .47086       7.163  .38439  .19057  4.2236  583.97
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   90.  580.69  3275.7   646.4   588.5       717.6   691.1    3.80   .9623  90.790      .10107  .60288  .22025   .4436  3.1920
            0.  73.593      0.      0.          C.  41.574     .98  310.21  .51209        .594  .31226  .10864  3.6702  601.47
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  130.  573.78  3172.0   630.9   638.8       829.2   658.3     .00   .9368  89.709      .09863  .58565  .23257   .4858  3.6375
            0.  74.620      C.      0.          C.  40.848     .00  301.99  .49594        .000  .33244  .10292  3.1711  589.98
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  170.  580.97  3180.2   618.5   620.4       832.8   669.4     .37   .9502  90.333      .09671  .58805  .23487   .4846  3.0965
            C.  74.497      0.      C.          0.  41.574     .12  306.30  .49722        .058  .33186  .10472  3.8471  595.25
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

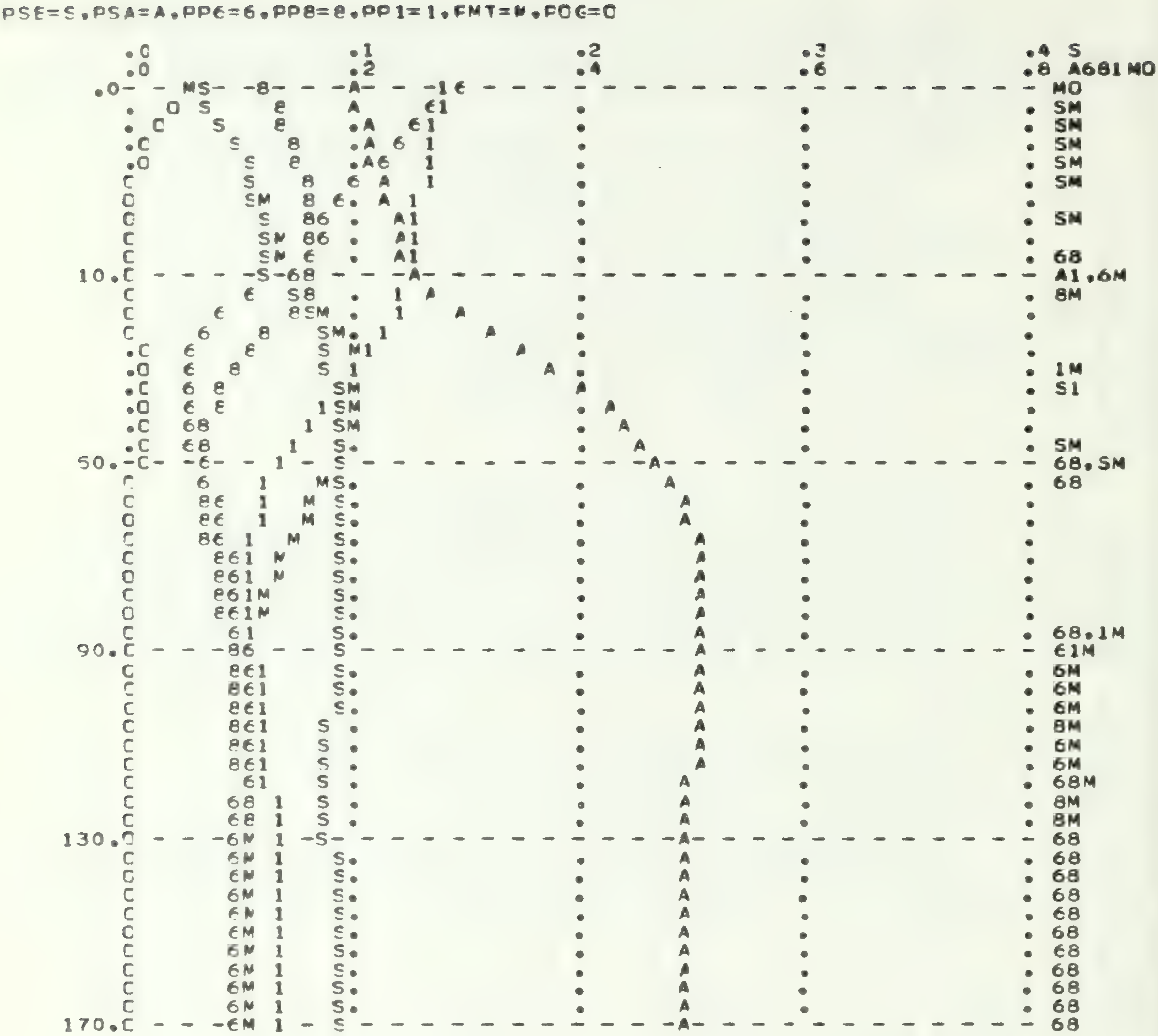

Figure 9.--The proportional distribution of habitats for the optimal deer mode of management.

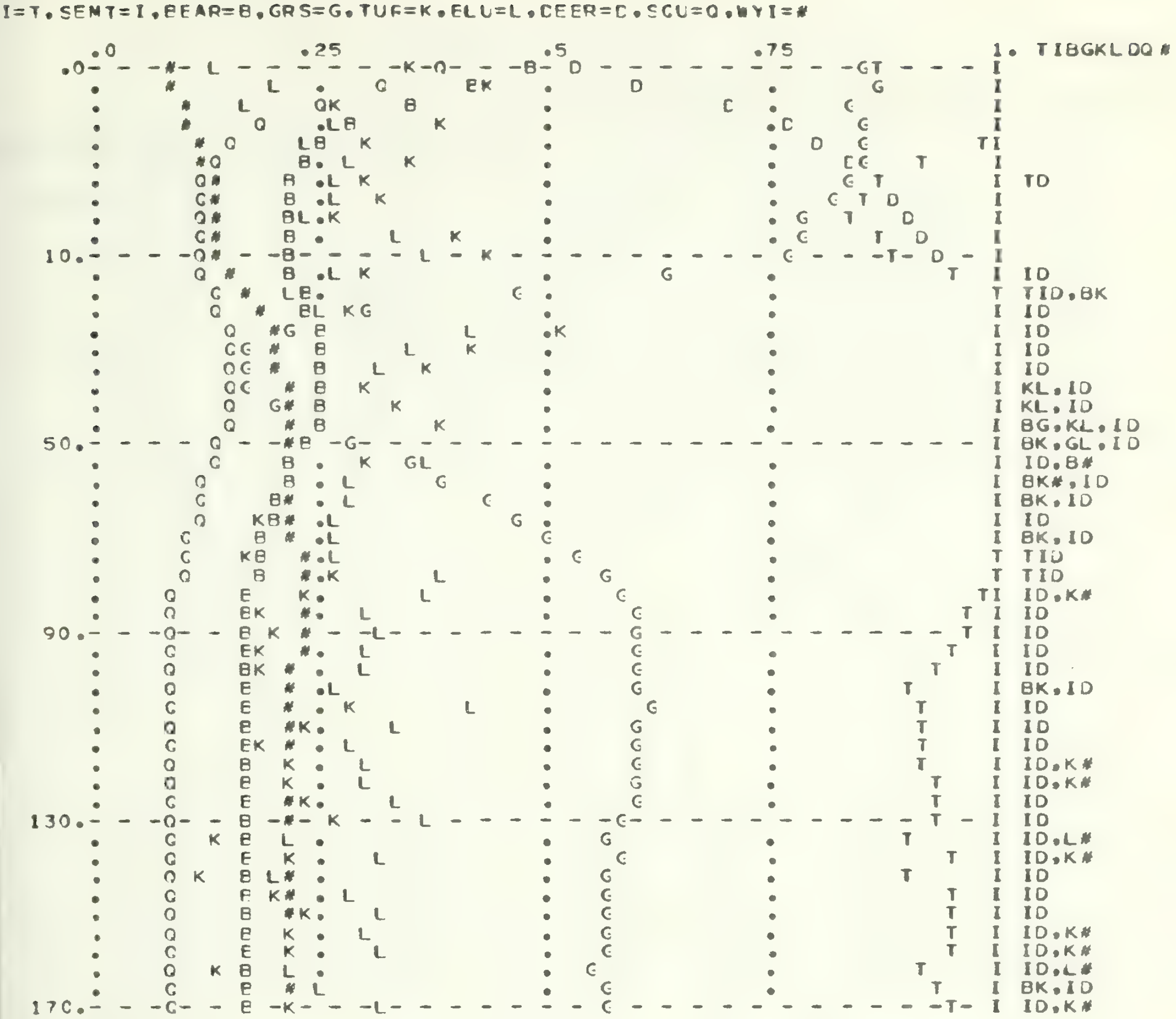

Figure 10.--The relative production, availability, or desirability of a group of benefits for the optimal deer mode of management.

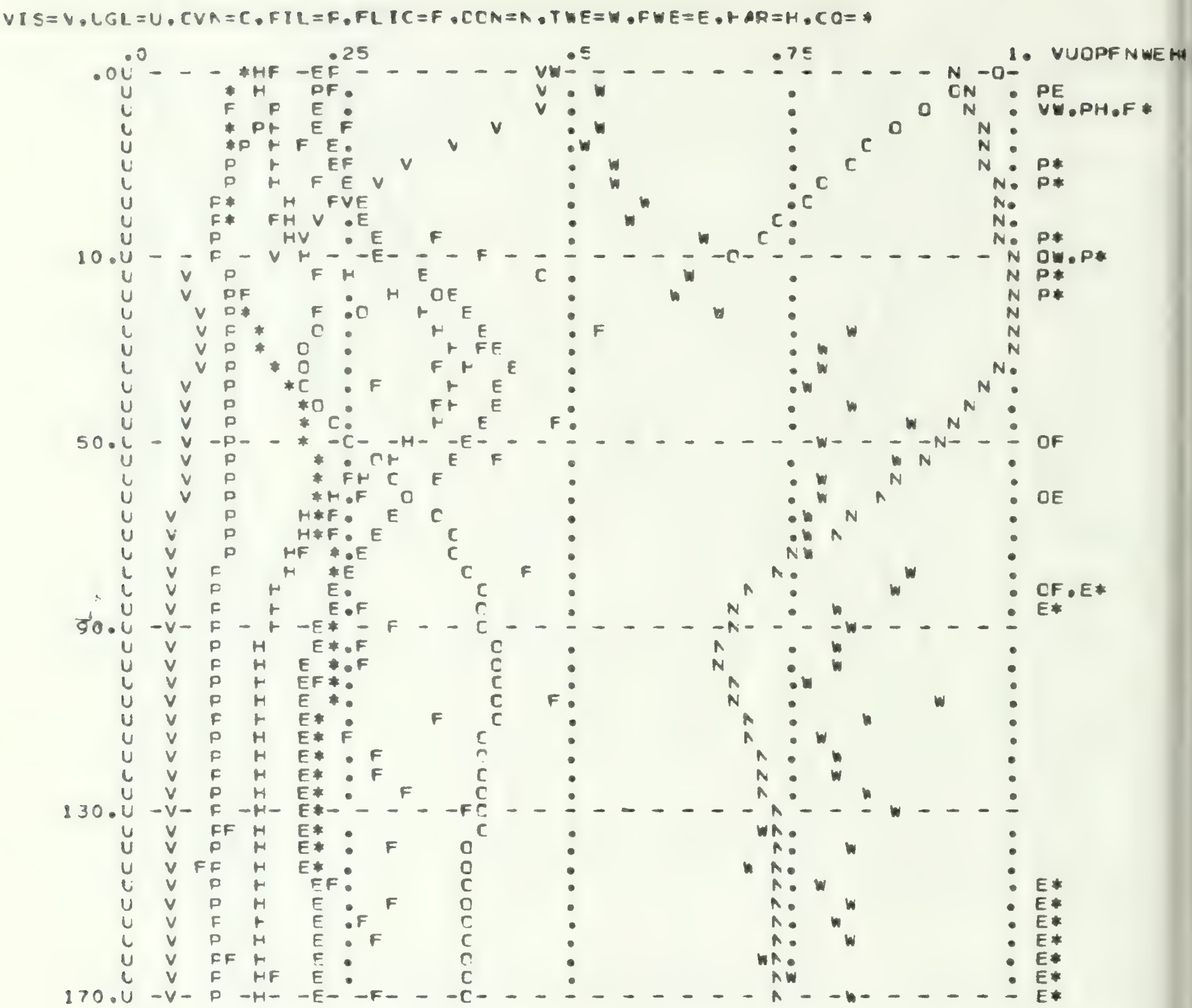

Figure 11.--The relative production, availability, or desirability of a group of benefits for the optimal deer mode of management.

Table 7.--The analytic silviculture controls for the mode of management designated "optimal squirrel and bear"

Habitat class	Harvest age	Fraction of forest area harvested in class
	Years	Percent
Mature timber	HMT = 120	MTF = 55
Old-growth	HOG = 300	OGF = 45

Initial size of harvested openings, ISO = 13.
Standard deviation of harvested openings, ISD = 1.

The optimal livelihood for bear and squirrel is achieved by using two superimposed rotation periods that harvest timber from both old-growth stands and mature timber stands. Since we want to provide large trees with cavities for bear dens, we begin by arbitrarily setting the age of harvest for old growth at 300 years. The rate of harvest for this very long rotation is inadequate to provide the necessary proportion of soft-mast habitat as seedlings and saplings. Since timber production is incidental to the optimum, we set the harvest age of mature timber at 120 years to provide the largest possible amount of hard mast before the trees are harvested. The next step is to determine the proportion of the total area that is to succeed through the two habitat classes in order to provide the desired state of forest organization. We therefore make several trial runs using 50 percent of the area succeeding through old growth and then varying the proportions between mature timber habitat and old growth by about 5 percent for the other runs. We examine the displays for the trial runs and select one that most nearly approaches the assumed optimum for squirrel and bear (table 7).

For the first 10 years, no timber is harvested from the old-growth habitats (table 8). Timber harvest for the mature timber habitats is delayed until the second year, when about 2 acres can be harvested. By the 10th year, about 23 acres are harvested from the mature timber habitats. When the distribution of habitats approaches the desired state of forest organization, sometime after 50 years, the rate of timber harvest is about 27 acres per year for mature timber habitats and about 10 acres per year for the old-growth habitats (table 8; fig. 12). The potential-timber index approaches about 0.6 of the maximum (fig. 13). The timber harvested is incident to developing an optimal livelihood for squirrel and bear. However, of some economic significance is the expected harvest of trees from stands 130 years and older. These trees would likely produce logs of large diameter and high value for certain hardwood products.

None of the habitats are unduly constrained, as indicated by the constraint quantum, which does not exceed a value of about 0.2. Although squirrel and bear are favored in this mode of management, deer, grouse, and turkey are not unduly constrained. The water-yield index is relatively low because of the small proportion of area in seedling and young sapling habitats. The ovenbird group of species, birds that benefit from a relatively large proportion of the area in sapling habitats, has the lowest potential livelihood of any of the animals considered (fig. 14).

3.6 Optimal Production of Water and Fiber

The perceived optimum is to produce the largest amount of water that is feasible without creating undue erosion and movement of sediment from the forest. A high yield of fiber as small-diameter stems is compatible with a high yield of water.

From the algorithms for water yield, Appendix B, it is readily apparent that a single rotation period of 15 years (table 9) would produce a high yield of water and maintain most of the area in sapling habitat. For the high rate of harvest required for this mode of management, the initial size of openings (ISO) is set at 50 acres in order to reduce the amount of roads and trails required. The initial standard deviation (ISD) is set at 5 acres. No consideration is given to other benefits.

Table 8.--Information about the state of the forest, over time, when managed with the optimal squirrel-bear mode

TIME	SFD SFS	SAF SAS	P6 P6S	P8 P8S	P1 P1S	NT NTS	OG OGS	PTI VT	PSL PSA	PPF PDG	PSEA PDBM	P1M PMD	BAL OPM	OPS WY
E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E-03 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00
.0	200.00 0.	1254.0 0.	1843.0 0.	740.0 0.	1808.0 0.	366.0 .000	185.0 .0000	.00000 .00	31.270 .19606	.28815 .02892	.22733 .45560	.33990 .08615	.8838 .00000	.000 215.64
1.	162.90 0.	1250.8 0.	1763.9 0.	810.7 0.	1768.6 0.	456.0 .000	185.0 .0000	.00000 .00	25.469 .19555	.27579 .02892	.22102 .47457	.34781 .10022	.9552 .00000	.000 191.08
2.	132.69 0.	1241.0 0.	1689.9 0.	872.1 0.	1735.4 0.	544.2 2.297	185.0 .0000	.00094 .30	20.745 .19402	.26421 .02892	.21477 .49275	.35641 .11401	1.0288 .10006	.110 170.60
3.	108.50 0.	1225.7 0.	1620.3 0.	924.6 0.	1707.7 0.	630.1 5.134	185.0 .0000	.01664 5.36	16.964 .19164	.25333 .02892	.20860 .51008	.36551 .12743	1.1042 .10006	1.212 153.71
4.	90.12 0.	1206.3 0.	1554.7 0.	969.3 0.	1684.8 0.	713.0 7.830	185.0 .0000	.04546 14.65	14.090 .18860	.24307 .02892	.20269 .52644	.37490 .14040	1.1810 .10006	3.022 140.34
5.	76.98 0.	1184.0 0.	1492.7 0.	1006.8 0.	1665.9 0.	792.8 10.397	185.0 .0000	.07806 25.16	12.035 .18512	.23338 .02892	.19716 .54182	.38441 .15287	1.2585 .10006	5.190 130.22
6.	68.35 0.	1160.0 0.	1434.1 0.	1037.9 0.	1650.3 0.	869.3 12.847	185.0 .0000	.11303 36.44	10.686 .18137	.22421 .02892	.19206 .55621	.39394 .16484	1.3362 .10006	7.515 122.95
7.	63.50 0.	1135.2 0.	1378.4 0.	1063.2 0.	1637.4 0.	942.8 15.169	185.0 .0000	.14867 47.92	9.928 .17749	.21551 .02892	.18742 .56964	.40341 .17632	1.4137 .10006	9.884 118.09
8.	61.74 0.	1110.3 0.	1325.6 0.	1083.3 0.	1626.8 0.	1013.2 17.827	185.0 .0000	.18408 59.34	9.653 .17360	.20726 .02892	.18325 .58213	.41276 .18734	1.4907 .10366	11.814 115.27
9.	62.54 0.	1086.0 0.	1275.4 0.	1098.6 0.	1618.0 0.	1080.7 20.663	185.0 .0000	.22183 71.51	9.777 .16979	.19941 .02892	.17957 .59370	.42194 .19789	1.5666 .10780	13.691 114.15
10.	65.57 0.	1062.7 0.	1227.7 0.	1109.7 0.	1610.6 0.	1145.2 23.352	185.0 .0000	.26145 84.28	10.251 .16615	.19195 .02892	.17640 .60435	.43085 .20797	1.6407 .12233	14.219 114.56
50.	137.78 0.	847.4 0.	490.0 0.	640.1 0.	1167.5 0.	2241.1 27.060	896.5 1.7342	.42537 137.12	21.541 .13248	.07661 .14016	.15402 .63301	.53292 .49054	2.7446 .31664	12.010 147.44
90.	176.57 0.	935.9 0.	450.2 0.	460.0 0.	728.0 0.	1961.5 27.060	1714.7 9.3614	.55427 178.67	27.606 .14632	.07038 .26809	.17393 .49242	.42050 .57476	2.0155 .30171	12.332 178.84
130.	187.90 0.	1067.6 0.	512.8 0.	491.2 0.	645.1 0.	1613.7 27.060	1908.3 9.5940	.56300 181.49	29.378 .16692	.08017 .29836	.19630 .42996	.35316 .55066	1.5552 .28974	13.050 195.15
170.	186.47 0.	1109.2 0.	548.1 0.	536.8 0.	690.4 0.	1515.1 27.060	1839.1 9.5940	.56300 181.49	29.154 .17342	.08569 .28754	.20257 .42875	.34483 .52442	1.4874 .30520	12.256 197.01

```
PSE=S,PSA=A,FP6=6,FP8=8,PP1=1,FMT=M,FCG=C
        .0             .1             .2             .3             .4 S
        .0             .2             .4             .6             .8 A681MO
      .0- O MS- -8- - -A- - -16 - - - - - - - - - - - - - - - - - - -
        . O SM    8    A     6        .              .              . 61
        . CS  M   8    A    6         .              .              . 61
        . OS   M   8  A.   61         .              .              .
        . S     M  8  A.  6 1         .              .              . SO
        . S      M  8 A.  6 1         .              .              . SO
        . S       M 8 A. 6 1          .              .              . SO
        .SC        M8A .6  1          .              .              .
        .SC         MA .6  1          .              .              . A8
        .SC          A 6   1          .              .              . A8M
     10.- S - - - - A86 - -1- - - - - - - - - - - - - - - - - - - - - 8M,SO
        . S         A8 .M  1          .              .              . A6,SU
        . CS       A 8 .  1           .              .              . A6,1M
        .  S      6A8  .  1 M         .              .              . SO
        .  SC    6A8   .  1   M       .              .              .
        .  S C  6 A8   . 1     M      .              .              .
        .  S  C6  A    . 1      M     .              .              . A8
        .  S   6 8A    .1        M    .              .              . 60
        .  S  6 C8A    1          M   .              .              .
        .  S  6 8OA   1.          M   .              .              .
     50.- -S- 6 8 A0- 1 - - - - - M - - - - - - - - - - - - - - - - -
        .  S  68  A C1 .          M   .              .              .
        .  S 6 8  A 10 .          M   .              .              .
        .   S68   A 1 C.          M   .              .              .
        .   S68   A1   C          M   .              .              .
        .   S68   A    .O        M    .              .              . A1
        .   S68   A    . C       M    .              .              . A1
        .   S68   A    .  O      M    .              .              . A1
        .   S68  1 A   .   C    M     .              .              .
        .   S6   1 A   .    C   M     .              .              . 68
     90.- - S6- -1-A- - - - C -M- - - - - - - - - - - - - - - - - - - 68
        .   S6  1  A   .     CM       .              .              . 68
        .   S6  1  A   .     CM       .              .              . 68
        .   S6  1   A  .     M        .              .              . 68,MO
        .   S86 1   A  .     MC       .              .              .
        .   S86 1   A  .     MC       .              .              .
        .   S 6 1   A  .    M C       .              .              . 68
        .   S 6 1   A  .    M C       .              .              . 68
        .   S 6 1   A  .   M  C       .              .              . 68
        .   S 6 1   A  .   M  C       .              .              . 68
    130.- - S 6 1 - -A- - -M- C - - - - - - - - - - - - - - - - - - - 68
        .   S 6 1    A .   M  C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
        .   S 6 1    A .  M   C       .              .              . 68
    170.- - S 6 1 - -A- - M - C - - - - - - - - - - - - - - - - - - - 68
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Figure 12.--The proportional distribution of habitats for the optimal squirrel-bear mode of management.

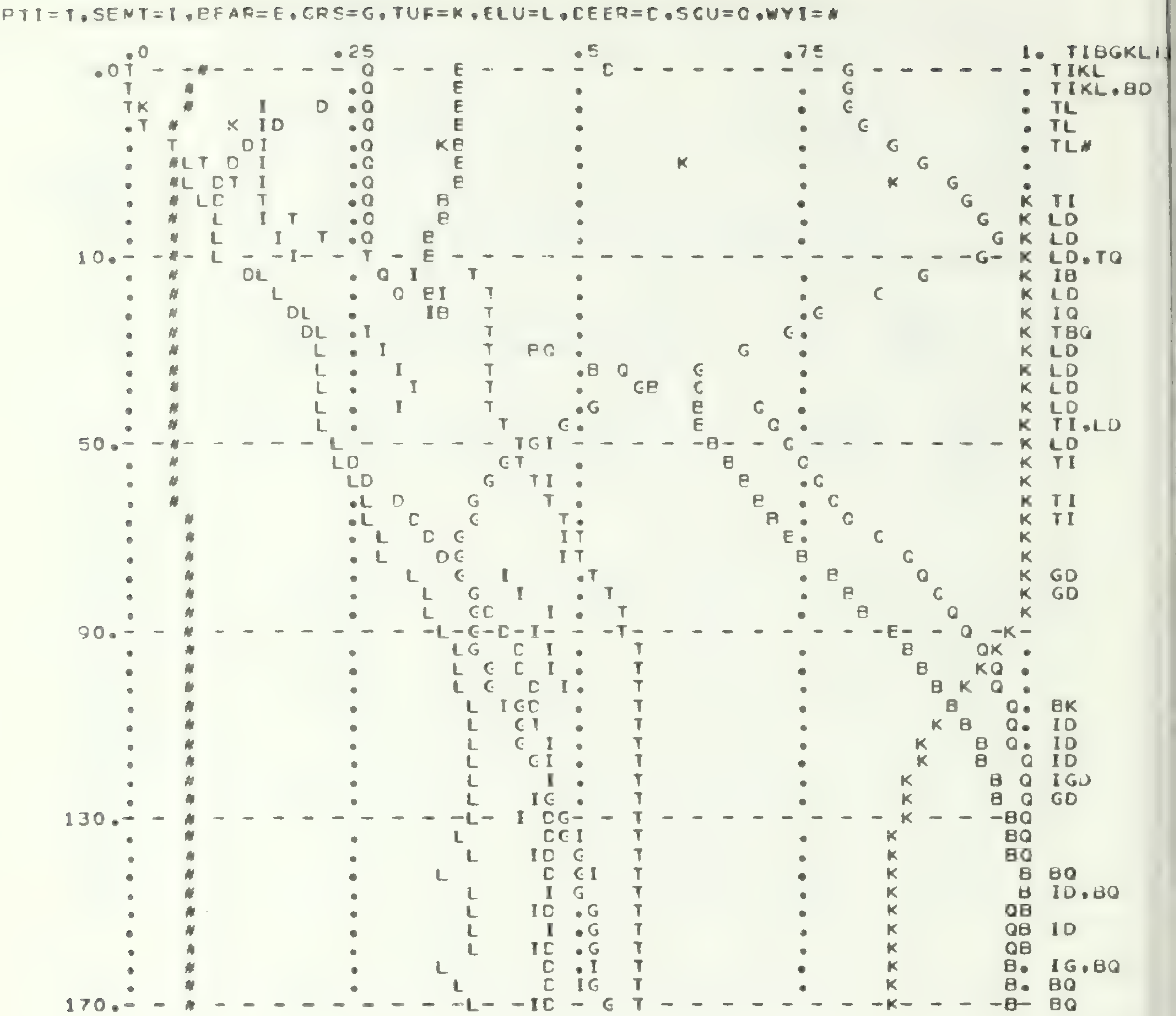

Figure 13.--The relative production, availability, or desirability of a group of benefits for the optimal squirrel-bear mode of management.

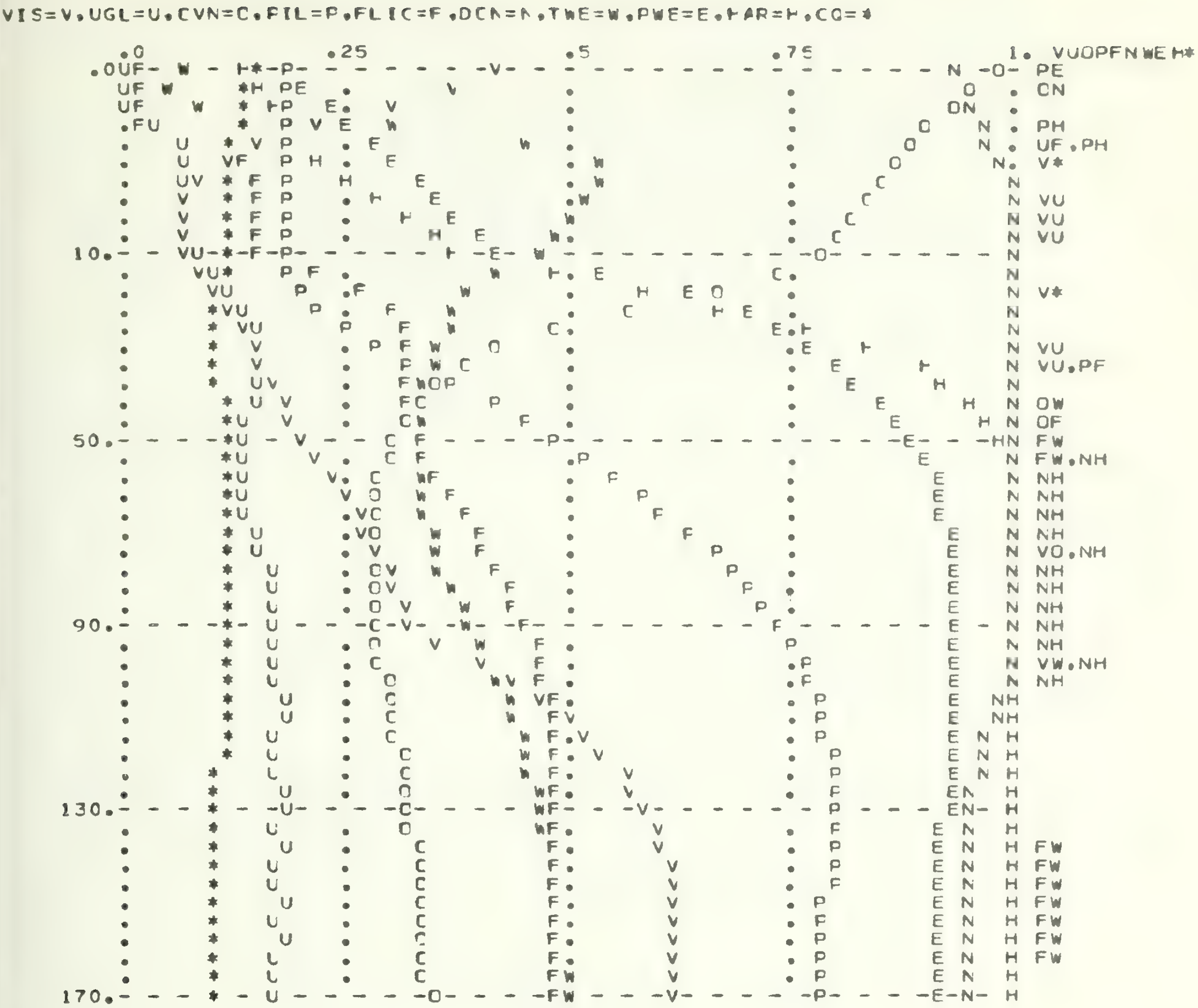

Figure 14.--The relative production, availability, or desirability of a group of benefits for the optimal squirrel-bear mode of management.

Table 9.--The analytic silviculture controls for the mode of management designated "optimal water and fiber"

Habitat class	Harvest age	Fraction of forest area harvested in class
	Years	Percent
Sapling	HSA = 15	SAF = 1

Initial size of harvested openings, ISO = 50.
Standard deviation of harvested openings, ISD = 5.

For the first 50 years, timber harvest is a process of liquidating all of the accumulated trees older than 15 years (table 10; fig. 15). From the 1st through the 10th year, the potential-timber index exceeds three times the sustainable maximum because of this rapid rate of timber removal. After the habitats are brought to the desired state of organization to provide high yields of water, the potential-timber index (PTI) is about 1.2; this index does not appear on the plot (fig. 16) because the value is greater than 1. Of course, the harvest consists entirely of small-diameter stems.

After the 10th year, the water-yield index is increased to about 0.65 of the maximum potential (fig. 16). For this particular area the yield increases sevenfold, to about 1,689 acre-feet of water per year (table 10). Sediment flow increases but stays below the maximum.

The constraint quantum rapidly increases to about 0.7, indicating a severe constraint on the distribution of habitats and on the livelihood for large numbers of plant and animal species (fig. 17). Still, some species benefit from this program. The bluebird index is above 0.75, and the habitat potential for the towhee group of birds is maximum. The habitat potential for flicker is only about 0.5 of the maximum, because of reduced pole and mature timber habitats for nesting. However, the intent of the optimum is to produce water and fiber and incidentally to produce some other benefits.

Table 10.--Information about the state of the forest, over time, when managed with the optimal water-fiber mode

```
  TIME     SED      SAP      F6       F8          F1      NT       OG      PTI      PSE          PP6    PSEA     PIM      BAL      CPS
           SES      SAS      P6S      P8S         P1S     M1S      OGS     VT       PSA          POG    PO8M     PMC      CPM      WY
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  E+00     E+00     E+00     E+00     E+00        E+00    E+00     E+00     E+00     E+00         E+00    E+00     E+00     E+00     E+00
           E+00     E+00     E+00     E+00        E+00    E+00     E+00     E+03     E+00         E-03    E+00     E+00     E+00     E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    .0    200.0   1254.0   1843.0   740.00      1808.0  607.40   370.00   2.8659   .03127      .28815   .2273   .37764   .95705   52.311
             0.      .00      .00      .00         .00  241.40   185.00    923.8   .19606      57.849  .49334   .15281    .4078    215.6
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1.    378.9   1300.4   1722.0   809.01      1767.4  545.88   275.40   3.7999   .05924      .26923   .2626   .36167   .91797   54.012
             0.      .00    75.51    75.51      108.37  196.67    64.45   1224.9   .20332      43.058  .48816   .12841    .7830    336.1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    2.    601.3   1381.8   1601.4   853.49      1703.6  452.29   183.73   4.2861   .09401      .25037   .3101   .33708   .83956   42.166
             0.      .00      .00    24.88      265.69  117.73    23.68   1381.7   .21605      28.725  .47052   .09944    .9186    487.5
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    3.    830.2   1507.9   1490.9   880.63      1569.7  366.72   117.14   4.4511   .12981      .23309   .3656   .30276   .73571   49.440
             0.      .00      .00    10.12      322.62   85.65     9.58   1434.9   .23376      18.314  .44044   .07565    .8887    646.2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    4.   1040.6   1679.3   1390.2   902.92      1373.3  293.49    73.51   4.4924   .16270      .21736   .4253   .26060   .62521   44.230
             0.      .00      .00     5.95      351.07   65.24     4.59   1448.2   .26256      11.493  .40177   .05738   1.0380    795.7
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    5.   1225.2   1892.1   1257.6   921.78      1134.6  229.35    46.05   4.4881   .19156      .20288   .4874   .21325   .51772   46.878
             0.      .00      .00     4.76      371.44   47.69     2.64   1446.8   .29583       7.201  .35736   .04306   1.0528    931.1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    6.   1383.0   2141.2   1212.0   936.69       869.6  171.01    28.96   4.4662   .21623      .18949   .5510   .16270   .41749   44.813
             0.    82.76    82.76    87.22      238.08   30.88     1.69   1439.7   .33477       4.527  .30915   .03127   1.1377   1051.4
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    7.   1515.5   2414.2   1121.8   927.29       623.8  118.57    18.22   4.2506   .23694      .17538   .6144   .11606   .33052   44.874
             0.      .00    29.55   275.70      110.47   16.32     1.06   1370.2   .37746       2.849  .26104   .02139   1.1110   1156.7
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    8.   1632.0   2714.6   1027.9   836.74       438.3   78.61    11.38   4.0502   .25515      .16072   .6796   .08082   .25187   41.507
             0.      .00    11.97   342.99       64.33    8.32      .61   1305.6   .42442       1.780  .21164   .01407   1.2084   1253.4
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    9.   1727.4   3040.1    943.6   672.71       300.5   51.09     7.05   3.8532   .27007      .14752   .7454   .05497   .17935   49.479
             0.    79.43   118.31   205.50       37.75    4.50      .34   1242.1   .47531       1.102  .16015   .00909   1.1002   1337.9
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   10.   1799.0   3370.7    844.1   496.04       197.2   32.76     4.34   3.4912   .28128      .13197   .8083   .03595   .12072   52.437
             0.    27.07   285.87    97.36       19.08    2.49      .18   1125.4   .52701        .679  .11351   .00580    .9834   1407.1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   50.   2098.1   4646.3       .0      .00          .0     .00      .00   1.1678   .32803      .00000  1.0545   .00000   .00000   47.510
             0.   419.61      .00      .00         .00     .00      .00    376.4   .72643        .000  .00000   .00000    .9997   1689.2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   90.   2098.1   4646.3       .0      .00          .0     .00      .00   1.1678   .32803      .00000  1.0545   .00000   .00000   52.140
             0.   419.61      .00      .00         .00     .00      .00    376.4   .72643        .000  .00000   .00000    .8053   1689.2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  130.   2098.1   4646.3       .0      .00          .0     .00      .00   1.1678   .32803      .00000  1.0545   .00000   .00000   56.375
             0.   419.61      .00      .00         .00     .00      .00    376.4   .72643        .000  .00000   .00000    .7448   1689.2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  170.   2098.1   4646.3       .0      .00          .0     .00      .00   1.1678   .32803      .00000  1.0545   .00000   .00000   50.996
             0.   419.61      .00      .00         .00     .00      .00    376.4   .72643        .000  .00000   .00000    .8233   1689.2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
PSE=S.PSA=A.PP6=6.PP8=8.PP1=1.FMT=M.PCG=C

    .0             .1             .2             .3             .4 S
    .0             .2             .4             .6             .8 A681M
  .0- - OS-M-8- - -A- - -16 - - - - - - - - - - - - - - - - - - -
    .  O  M  S     A    61        .              .              . S8
    . C  M    8   S.A  61         .              .              .
    .C  M     8    . 6AS          .              .              . A1
    .C M       8   .6   A   S     .              .              . 61
    .O M       8 1 6      A      S.              .              .
    C M       18  6.         A    . S            .              .
    CM     1   8 6 .            A .     S        .              .
    CM   1    8 6  .              . A     S      .              .
    CM  1   8  6   .              .     A    S   .              .
 10.M 1 - 8 - 6 - - - - - - - - - - - - - - A S - - - - - - - - - MO
    186            .              .              .S      A      . 1MO
    6              .              .              . S       A    . 681MO
    6              .              .              .   S     A    . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
 50.6 - - - - - - - - - - - - - - - - - - - - - - - -S- - A - - - 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
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    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
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    6              .              .              .   S    A     . 681MO
130.6 - - - - - - - - - - - - - - - - - - - - - - - -S- - A - - - 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
    6              .              .              .   S    A     . 681MO
170.6 - - - - - - - - - - - - - - - - - - - - - - - -S- - A - - - 681MO
```

Figure 15.--The proportional distribution of habitats for the optimal water-fiber mode of management.

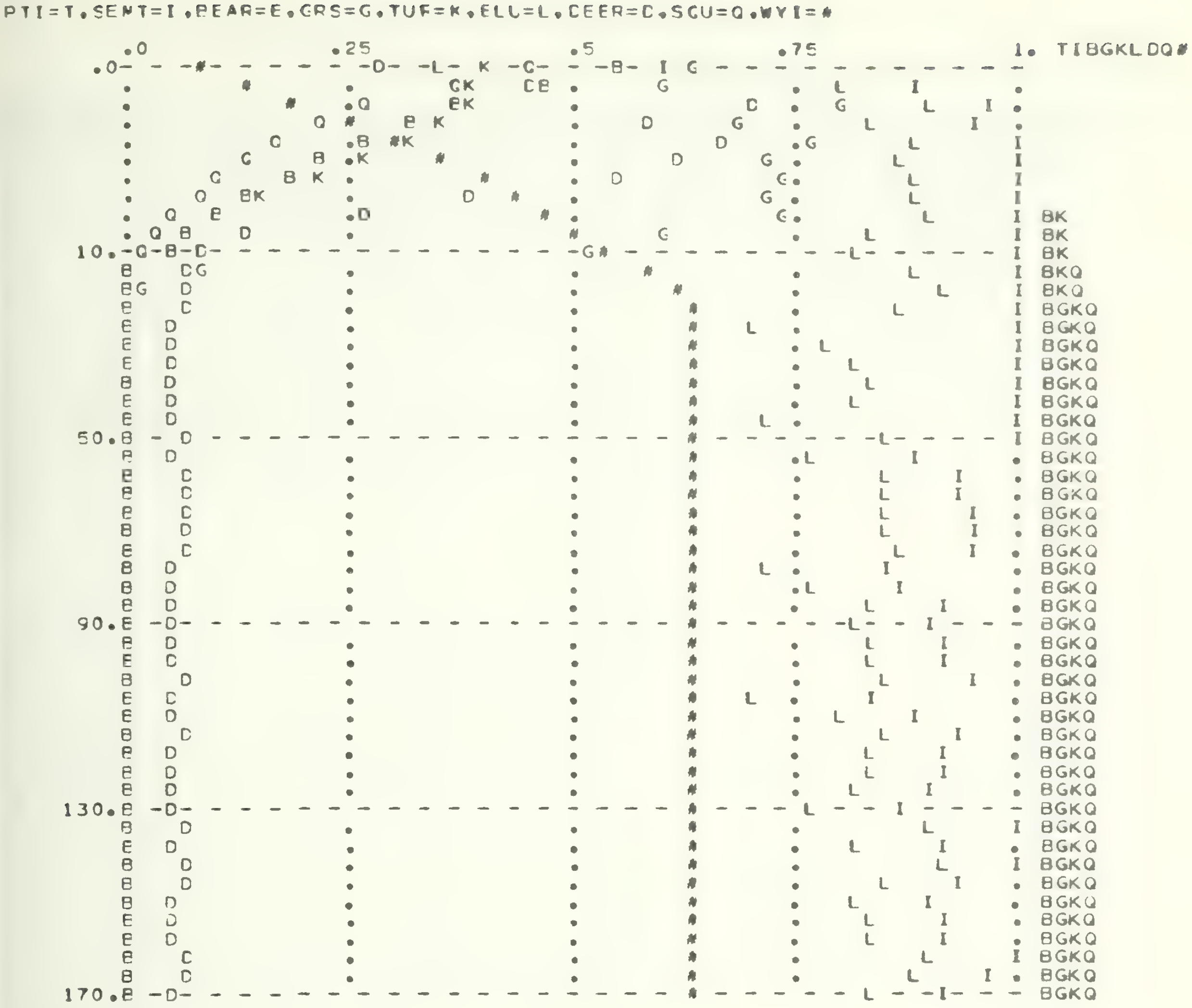


Figure 16.--The relative production, availability, or desirability of a group of benefits for the optimal water-fiber mode of management.

```
VIS=V,UGL=U,CVN=C,PIL=P.FLIC=F,DCN=N,TWE=W.PWE=E.HAR=H,CO=*

    .0            .25             .5            .75             1. VUOPFNWEH
  .0- - -*- - - -U- P E - - - - - FV- -W- - - - - - - - - - -O- ON.UH
    .  U*      H  PE   V          .      W       .         FO N .
    .U  *V   H PE  .              .         W    .        O N   . OF
    .U  *V  HP E   .              .              W     FC N     .
    .U  V*H PE     .              .              .   FC         . FNW
    .U  V  HP E    .              .        N     .F C  W        . H*
    .U V H PE      .           N  .          F   . C     W      . E*
    .U VH  P  *    .    N         .       F      O          W   . PE
    .U VH PE     * N              .    F       C .            W .
    .UV H PE  N    .*             .  F       O   .              W
 10.-UVH- P N - - - - - * - - - - - F - O - - - - - - - - - - - W PE
    .UVH  P  O     .              F    *         .              W PNE
    .UVH  PC       .              F         *    .              W PNE
    .UVH  C        .              F          *   .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W CPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
 50.-UVH- C - - - - - - - - - - - F - - - - - * - - - - - - - - W OPNE
    . VH UC        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    . VH  C    U   .              F           *  .              W OPNE
    . VH  CU       .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
 90.-UVH- C - - - - - - - - - - - F - - - - - * - - - - - - - - W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    . VH  C        U              F           *  .              W OPNE
    . VU  C        .              F           *  .              W OPNE.UH
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W CPNE
130.- VH- CU- - - - - - - - - - - F - - - - - * - - - - - - - - W OPNE
    .UVH  O        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W CPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
    .UVH  C        .              F           *  .              W OPNE
170.-UVH- C - - - - - - - - - - - F - - - - - * - - - - - - - - W OPNE
```

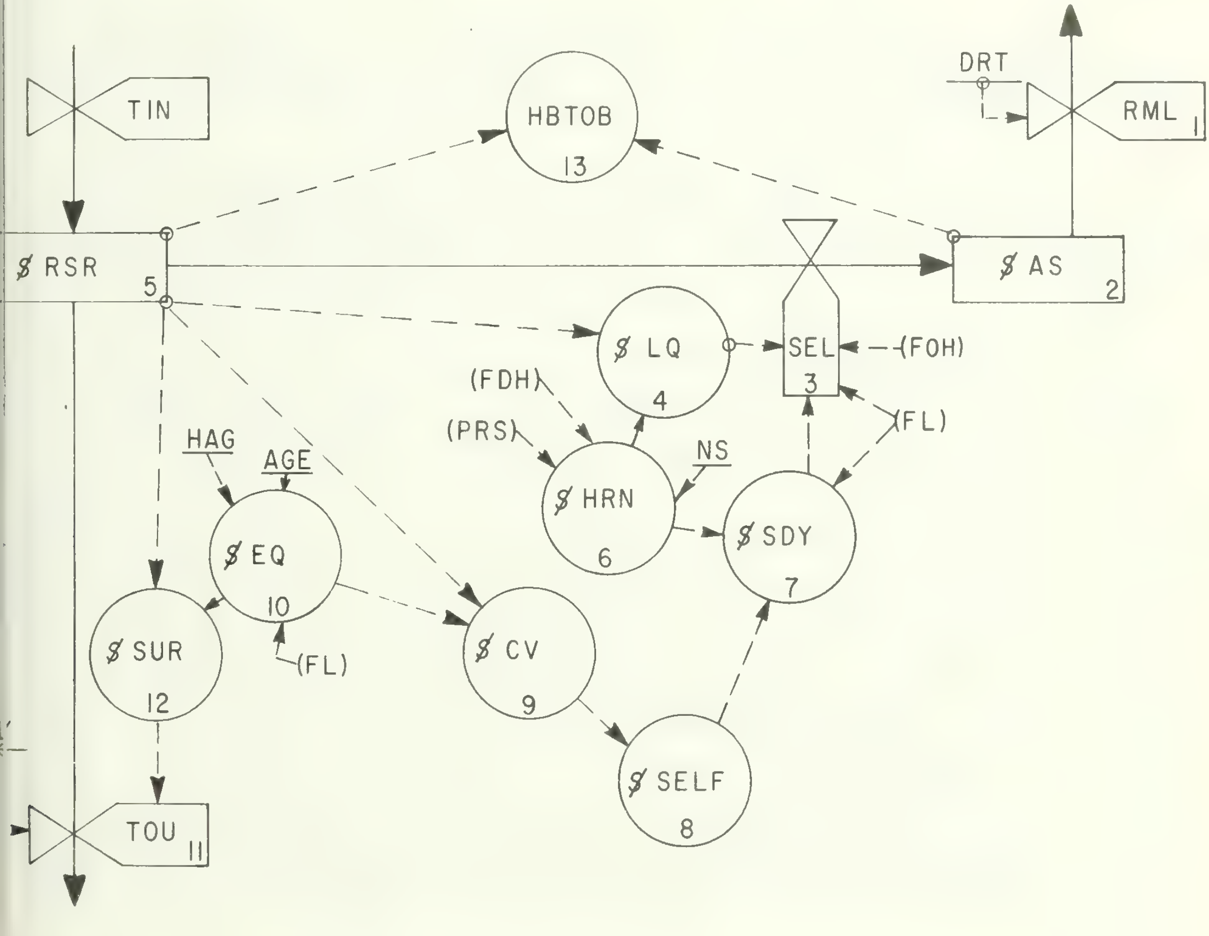
Figure 17.--The relative production, availability, or desirability of a group of benefits for the optimal water-fiber mode of management.

4. THE CORE AND BENEFIT EQUATIONS

DYNAST-OB is composed of two groups of equations. One group, called the core, models ccessive changes in the states of organization of the forest over time as regulated by the de of management. The other group models the availability of benefits by linking benefit gorithms to the state of organization of the forest. In this section, the structure of the re group of equations is described and the benefit equations are related to the core. Non-chnical readers may be interested chiefly in section 4.6, which discusses management of a rest divided into multiple categories.

l Equations and Flow Charts

Equations for the model are written for the DYNAMO II simulation compiler (Pugh 1976). is compiler is especially useful for revealing the systemic behavior of models with feed-ck loops and integration equations (Forrester 1961, 1968). The relationship of the equa-ons to the model and the structure of the feedback loops is here illustrated by a flow agram of one of the information networks (fig. 18). In this diagram, arrows indicate the



ıre 18.--A flow chart for the MACRO HBTOB, which computes changes in the area of a kind of habitat over time (sec. 4.3).

ection of flow. Solid lines indicate changes in the inventory resulting from the harvest timber and the succession of habitats, while dashed lines indicate a flow of information ıt the inventory and other parts of the system. Rectangles indicate the amount of area ıpied by the different age classes of the amount earmarked for sale and harvest. These ıs are computed by level equations identified by "L". Diagrams of "valves" indicate rate equations (R) that describe the changes in the system (succession, sales, and removals) for each interval of computation. To clarify the structure of the model, some of the rate calculations are put in auxiliary equations (A), diagramed as circles. Straight lines under the abbreviations indicate constants; these are assigned in C-type equations or computed as initial values in N-type equations. The equations are identified in parenthetical references by number and type; e.g., (Eq. 3,R). The equations, with definitions of terms, are listed in Appendix B.

Each variable has a name and an abbreviation in the DYNAMO notations. The subscript J, K, or L following a decimal point identifies the time of the variable's value. Three successive junctions of computation intervals (DT) are designated for each iteration. K is present Rates are constant over each computational interval and are subscripted JK for the past interval and KL for the next interval. Variables computed by level and auxiliary equations are subscripted J and K because they have values only for past and present times. An alphabetical list of variables, definitions, and units of measure are listed in Appendix C. The DYNAST-OB program is listed in Appendix A.

4.2 MACRO's

The number of equations required for the model can be greatly reduced when a series of similar equations can be replaced by a single function. In the DYNAMO notation, such a function is called a MACRO. Each MACRO has an abbreviation that is used in an equation whenever a particular series of computations is to be made.

For example, a number of different parts of the model are required to have a positive value. Rather than writing several equations for each instance, a MACRO is prepared and given the abbreviation PSTV. Whenever a computation is to maintain a positive value for some variable, i.e., X, one inserts into the appropriate equation PSTV(X). For DYNAST-OB, positive value is defined as equal to or larger than 1×10^{-6} (Appendix A, maintain a positive value).

The primary use of MACRO's in DYNAST-OB is to provide flexibility and efficiency in adapting the model to multiple forest types and other categories (sec. 4.6). The core model for DYNAST-OB is composed of two MACRO's, one for habitats and one for forest types. When there are two or more forest types, productivity classes, or other different conditions, the model is simply expanded by using the MACRO's (sec. 4.6).

4.3 HBTOB, MACRO for a Habitat

For each kind of habitat (age or size class), the model provides a set of feedback loop that control the rate of harvest and the rate of succession from this habitat. The rates of harvest and succession are regulated by the availability of the habitat; that is, if the are in a particular habitat is less than the amount required for the desired state of organization, the harvest rate is appropriately delayed on a sliding scale; if the amount of the habitat is more than the desired proportion, its harvest rate is accelerated. Also, a portion of the habitat transforms, in time, to the next older class.

The MACRO HBTOB computes changes in the area of a habitat over time (fig. 18). The are is the sum of the reserve accumulation of the habitat ($RSR) and the accumulated sales ($AS) (fig. 18, Eq. 13,A[2]). The accumulated sales ($AS) are reduced by the amount of habitat removed by harvest (RML) and increased by the rate of sales (SEL) (Eq. 2,L). The rate of harvest is the amount of accumulated sales ($AS) divided by the delay for sale and removal of timber (DRT). The latter value is a constant that is adjusted to reflect differences among forests.

The amount of a habitat to sell (SEL) is determined according to the mode of management as specified by the analytic silviculture controls. The choice to be made by the feedback loops is whether to liquidate the habitat ($LQ) or to bring it to the steady state ($SDY) required by the mode of management.

---

[2] See Appendix B for definitions of the equations.

Liquidation of a habitat occurs when neither this nor any older habitat is to be retained at steady state. An example is the liquidation of habitats in the mode for optimal water and fiber (sec. 3.6). The equation for rate of sales (SEL) (3,R), chooses liquidation when no harvest is specified by the silviculture controls for this or older habitats. Thus, when the flow of area for harvest (FL) from the habitat is 0 and the flow of area for all older habitats (FOH) is 0, the function FIFZE chooses a rate of harvest ($LQ) that rapidly liquidates the particular habitat.

The rate of sale for liquidation of a habitat is limited by the reserve accumulation ($RSR) and the harvest required from the habitat ($HRN, Eq. 4,A). The minimum function (MIN) results in the sale (SEL) eliminating the habitat if the reserve accumulation ($RSR) is smaller than the harvest required ($HRN). Until this final elimination, the sale (SEL) amount is limited by the amount of previous sales from older habitats (PRS, Eq. 6,A).

The harvest required is 0 for liquidation of a habitat ($HRN) if sales from older habitats (PRS) exceed the total sales permitted from all habitats (FDH). FDH is the amount of harvest that is needed to create the correct balance of habitats in the future, as derived from the controls. When FDH exceeds PRS, the harvest ($HRN) is that required to make up the difference between the sales from the older habitats (PRS) and the total required to bring the distribution of habitats to the desired mode of management (Eq. 6,A). When there are no sales from older habitats, the harvest required for liquidation is limited to $HRN, or the habitat is eliminated (Eq. 4,A).

The preceding set of equations is important because liquidation of older habitats is achieved smoothly and efficiently without creating large oscillations in the distribution of habitats. Large and continuous oscillations, such as could occur without the preceding feedback loops, could increase by a factor of 2 or more the time required to bring the distribution of habitats to the desired steady state.

When the age for harvest indicated by the controls is equal to or greater than the age of the habitat under consideration, a different set of loops regulates annual sales to bring the habitat to a steady state. The habitat will eventually occupy its appropriate fraction of the forest area, and stands of the designated age will be available for harvest each year at a rate that can be sustained indefinitely ($SDY). This mode operates in cases where FL + FOH is greater than 0.

4.4 OBTAH, MACRO for the State of a Forest Category

Forests are classified by types, productivity classes, and other different conditions. Each of these categories has different kinds of habitats. Habitats may change from one category to another by cultural actions or by natural forces. While the previously discussed MACRO HBTOB regulates harvest for a particular habitat and computes changes in its area, the MACRO OBTAH monitors the changes of state from one habitat class to another, through harvest, succession, and natural mortality. Thus it models the changing organization of the larger forest area or category (fig. 2). OBTAH's can also coordinate multiple categories and display the results of such a complex pattern of management (sec. 4.6).

The MACRO OBTAH uses the MACRO HBTOB for each habitat that is defined within a forest category (fig. 19). Consider, for example, the mode of management designated "optimal combination" (sec. 3.3). It was applied to a sample forest of a single category, an oak-hickory forest on 6,396 acres in North Carolina (sec. 3.1), for which seven kinds of habitat were defined (sec. 2.7). The cultural actions for this mode of management are to harvest mature timber at age 100 and have 70 percent of the area flow through the 100-year rotation; the remaining 30 percent of the area is to flow into the old-growth habitat and be harvested at age 200 (table 3). Guided by these controls, the MACRO OBTAH projects the changing state of organization, or proportion of habitats, from the inventory at time 0 to future times and shows what equilibrium can be reached under this mode of management (fig. 6).

The structure of the MACRO OBTAH is essentially the same as the core model for DYNAST-MB (fig. 19). Negative feedback loops have the goal of bringing about and maintaining the state of forest organization that provides the desired optimal combination of benefits. Harvest can be from any habitat and simultaneously from any combination of habitats. The equations for these negative feedback loops are listed in Appendix A and the equations and variables are defined in Appendixes B and C.

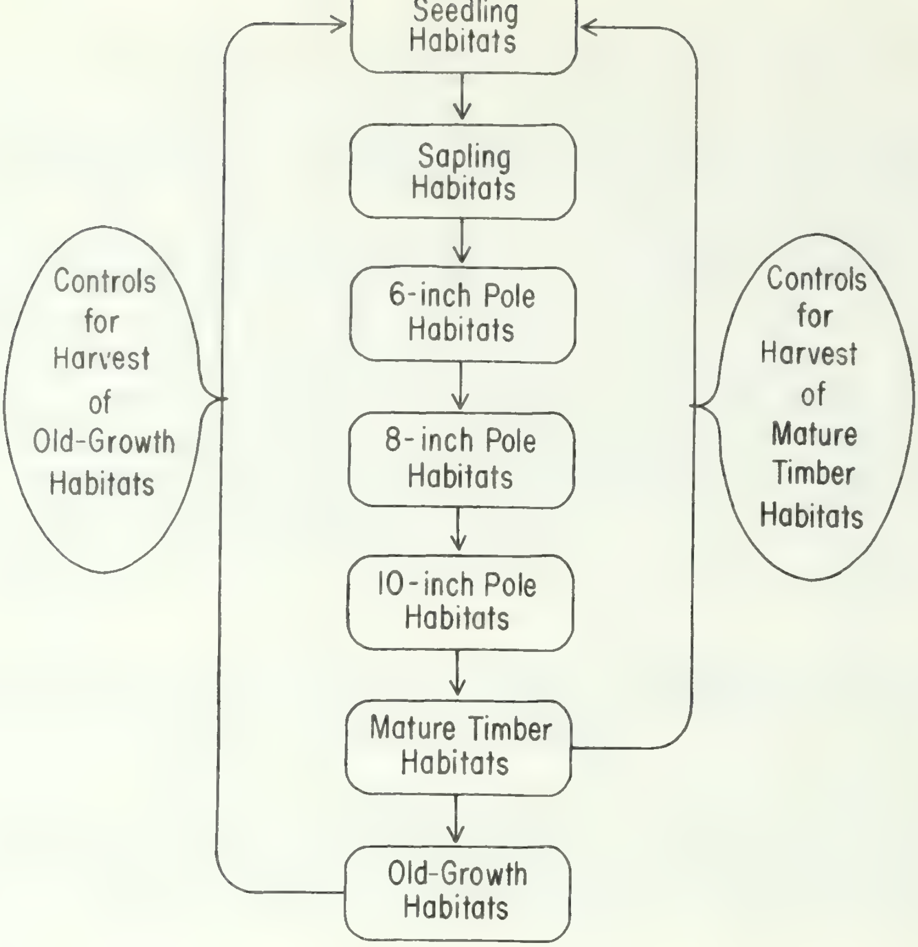


Figure 19.--The MACRO OBTAH uses the MACRO HBTOB (fig. 18) for each habitat. The overall structure of the MACRO OBTAH is the same as the core model for DYNAST-MB (Boyce 1977).

For each forest type or other category, the category is identified and certain constants are provided. This is done with an equation (Appendix A, Forest Type Sector; Eq. 2). The left side of the equation identifies the category "BIVY," the code for the Big Ivy Watershed (sec. 3.1), which is the only category in the example. On the right side of the equation, OBTAH identifies the MACRO. The codes ISE through OIG identify the acres of land initially in each of seven habitats. The values, taken from the inventory (table 11), are specified on a special card (Type C, Appendix A).

Table 11.--The relation of diameters, ages, delays, and the inventory values to habitats for the Big Ivy Watershed, Pisgah National Forest, North Carolina

Habitat[1]	Median diameter	Age range	Delay	Inventory
	Inches	Years	Years	Acres
Seedling	0-1.0	0-5	5	200
Sapling	1-4.9	6-35	30	1,254
Pole-6	5-6.9	36-50	15	1,843
Pole-8	7-8.9	51-65	15	740
Pole-10	9-10.9	66-85	20	1,808
Mature	11-15.9	86-120	35	366
Old-growth	16+	121-300	180	185

[1] Defined in section 2.7.

The codes CSE through COG identify rates of conversion of the category to some different category. For this illustration the equations for these values are set at 0 (Appendix B, Eqs. 3-9).

The delays for transformation from one habitat to another (table 11) are coded DSE to DOG. The values, in years, are specified in a C card.

The ages for harvesting trees from each habitat are coded HSE to HOG, and the proportions of the forest that are to rotate through each habitat are coded SEF to OGF. These variables are part of the analytic silviculture controls (Appendix A, end of the listing). For the mode of management designated "optimal combination," HMT = 100, MTF = 0.7, HOG = 200 and OGF = 0.3 (table 3), while values for the other habitats are 0.

The sizes of openings to be formed by harvesting are also specified in the analytic silviculture controls. For this illustration the codes ISO and ISD are used for the size of opening desired and the standard deviation permitted. These codes are used in the MACRO OBTAH and in the analytic silviculture control cards.

The MACRO OBTAH computes the cubic volume of timber that would be removed from each habitat in relation to the mode of management. For the mode "optimal combination," timber would be removed only from the mature and old-growth habitats. Other modes, such as "optimal deer" (table 5), may harvest timber from other habitats. The timber volumes are obtained from a yield table for the area. The yield table is converted to a set of indices by dividing the yields found in the yield table by the volume of timber at the age for culmination of mean annual increment (YST). The indices for timber yields are specified on a table (T) card. The yield standard (YST) and the age of culmination of mean annual increment (TMR) are specified on control cards.

After each iteration of the program for the time specified by DT (Appendix A, Program Control Sector), information about the state of organization of the forest type, or other category, is made available. For example, the amount of area for each habitat that should be sold (harvested) for timber is computed. This area is determined by the mode of management and the state of the forest at each iteration. For the "optimal combination" mode, these acreages to be harvested are printed in table 4 under the codes SES through OGS for the respective habitats from seedlings to old growth. For this mode of management, sales are permitted from only the mature and old-growth habitats.

The potential-timber index (PTI) is computed, printed in the table, and plotted with some other benefits. The total volume of timber (VT) expected to be harvested is also printed in the table for each mode of management. The number of openings (NOP) and the distribution of opening sizes (OPS) are computed. These can be printed or plotted if desired. For the illustrations used here, the values of these variables are made available for use in the benefit equations.

Finally, the area of each habitat is computed and coded SED, SAP, P6, P8, P1, MT, and OG for the habitats "seedling" through "old-growth," respectively. The values are printed in the tables and the proportional distributions of the habitats are plotted. The area and the proportion of area in each habitat in conjunction with the size of openings are the most important variables for describing the states of forest organization over time. These variables are used to estimate the potential availability of all benefits.

4.5 The Benefit Equations

The benefit equations are structurally independent of the core equations except that they use the output of the core model. The benefits depend entirely on the state of organization of the forest (Boyce 1978b). Thus, the computation of benefits is a matter of relating each benefit to the state of the forest, or proportion of habitats. Once these relationships or algorithms are determined by research and experience, benefits can be projected into the future in relation to changes in the state of the forest. The method is described in detail in previous publications (Boyce 1977, 1978b; Boyce and Cost 1978).

The illustrations used here (sec. 3) include all the benefit equations previously described for DYNAST-MB and DYNAST-TM (Boyce 1977, 1978a). Two additional algorithms are used in the DYNAST-OB. One of these, the constraint quantum, is described by Boyce and Cost (1978). The other algorithm was developed for water by Lloyd Swift, Southeastern Forest Experiment Station. The equations for the water-yield index (WYI) are listed and defined in Appendixes B and C.

There are several important points about the benefit equations:

1. The core equations are not dependent on any of the benefit equations.

2. Benefit equations can be included in, modified, and removed from the DYNAST-OB model without affecting any of the other benefit algorithms and without affecting the core equations.

3. Algorithms can be written for any benefit that can be related to the state of organization of the forest. The important variables are the distribution of forest stands within forest types, by age and area classes, the rates of timber harvest, and the size of openings formed by the harvest of timber.

4. The modes of management determine the states of organization which, in turn, determine the combinations of benefits.

5. The equations for benefits can be easily written and adjusted as new knowledge becomes available.

4.6 Use of the MACRO OBTAH for Multiple Categories

This section illustrates the use of the MACRO OBTAH when a forest is classified into several categories. The example is a ranger district on the George Washington National Forest in Virginia. To limit the size of the illustration, only four categories of the hardwoo portions of the forest are considered.

The purpose for the analysis is to identify one or more modes of management that provid biologically possible and desirable combinations of multiple benefits. Certain constraints limit the consideration of all possible modes of management. For example, portions of the ranger district are inaccessible for harvesting with currently available machinery, and portions of the district have such a low productivity that benefits are limited in both kinds and amounts. Thus, the forest is classified into medium sites and low sites and each site class has accessible and inaccessible areas. The inventory (table 12) describes the initial state of organization.

Table 12.--Inventory for hardwood stands, by site classes, habitats, and accessibility, for the Deerfield Ranger District, George Washington National Forest, Virginia

Habitat	Medium sites (SI 60)		Low sites (SI 50)	
	Accessible category 1	Inaccessible category 2	Accessible category 3	Inaccessible category 4
	Acres			
Seedling	578	1	33	--
Sapling	1,715	17	29	--
Pole-6	1,451	59	480	179
Pole-8	7,100	889	4,345	1,760
Pole-10	6,108	1,945	1,266	1,783
Mature timber	4,412	2,852	--	--
Old-growth	832	124	--	--
Total	22,196	5,887	6,153	3,722

Codes are used to identify each of the four categories. For example, DF1, DF2, DF3, and DF4 would identify the Deerfield Ranger District, categories 1, 2, 3, and 4. These symbols would be used on the left side of four different equations that used the MACRO OBTAH. The symbols on the right side of the equation, within the parentheses, can be coded by appending to the illustrated codes (Appendix A) the numbers 1, 2, 3, and 4 for each category. Then, the equations for category 1 would be written as follows:

A DF1.K = OBTAH (ISE1, ISA1, IP61, - - - - - - - P11.K, MT1.K, OG1.K)

DF1 identifies Deerfield, Category 1, medium site, accessible (table 12).

During the next period of management, 10 to 15 years, no portion of the categories is planned for conversion to another category, so the codes CSE1 through COG1, which indicate rates of conversion, are kept at 0 as indicated in Appendixes A and B.

The inventory values taken from table 12 are put on a C card as follows:

C ISE1 = 578/ISA1 = 1715 - - - IOG1 = 832.

The delays for the medium sites are found to be the same as for the Big Ivy Watershed. The same values, as illustrated in Appendix A, are used on the C card for codes DSE1 through DOG1.

The timber-yield index (TTYI1), yield standard (YST1) and age for culmination of mean annual increment (TMR1) are found to be the same for the George Washington medium sites as for the Big Ivy Watershed.

Equations are written in a similar way for categories 2, 3, and 4. Some different constants must be used on the C cards for the low-site areas. For example, very few, if any, of the stands on the low sites ever grow to diameters larger than the 10-inch-diameter class. Thus, the values for the inventories and for the harvest of mature timber and old-growth habitats would always be 0.

Delays, timber-yield indices, yield standard, and age for culmination of mean annual increment for the low sites are obtained from inventories and from data that are available at the ranger district.

Analytic silviculture controls must be specified for each of the four categories. The codes illustrated in Appendix A can be appropriately modified by appending the numbers 1, 2, 3, and 4. For the first mode of management, possibly designated "wilderness," all analytic silviculture controls should equal 0. Reruns for different modes require changing only a few of the variables.

The modes of management are limited in a number of ways. The analytic silviculture controls for the two inaccessible categories are always 0 because no timber can be harvested from these areas until different kinds of harvesting equipment become available. The low-site, accessible category (3, table 12) is most efficiently managed with one rotation period, because of the small sizes of even the oldest trees. Two superimposed rotation periods may be needed, and these are possible, for the medium-site, accessible category (1, table 12).

The most desirable combination of benefits that is biologically possible is determined by manipulating the analytic silviculture controls for the two accessible categories. The final choice of a mode for the next period of management is the one that most nearly approximates the subjectively perceived optimum.

4.7 Supplementary Information

Equations 10 through 21 listed under "Supplementary Information" (Appendix A) are used to compute percentages of the habitats which are plotted and to compute values that are needed for the benefit equations.

When there is more than one category, the supplementary equations are changed to compute the appropriate values for the benefit equations. For example, the percentage of area in the seedling habitat for the 4-category example (sec. 4.6) would be written:

A PSE.K = (SED1.K + SED2.K + SED3.K + SED4.K)/(DF1.K + DF2.K + DF3.K + DF4.K).

The primary concern is to display information in the plots and in the tables so as to provide a rational basis for selecting a mode of management. Displays can be for each category or for an aggregation of several or all categories. The displays provide information in a format that can be used to choose the mode of management that most nearly provides the perceived optimum.

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APPENDIX A

A LIST OF THE DYNAST-OB EQUATIONS

```
        *   DYNAST-OB 16 B.IVY ST
        NOTE
        NOTE  MAINTAIN A POSITIVE VALUE
        MACRO PSTV(X)
 1      A   PSTV.K=MAX(X.K,1E-6)
        MEND
        NOTE
        NOTE  MAINTAIN A VALUE EQUAL TO OR GREATER THAN UNITY
        MACRO UNTY(X)
 1      A   UNTY.K=MAX(X.K,1)
        MEND
        NOTE
        NOTE  MAINTAIN A VALUE EQUAL TO OR GREATER THAN ZERO
        MACRO ZERO(X)
 1      A   ZERO.K=MAX(X.K,0)
        MEND
        NOTE
        NOTE  STATE OF A HABITAT TYPE (HBTOB)
        MACRO HBTOB(TIN,PRS,FL,FOH,FDH,INV,DLY,AGE,HAG,TTYI,YST,SO,
        X   TOU,SEL,RML,VRM,SOH,NC)
 1      R   RML.KL=($AS.K/DRT)
 2      L   $AS.K=$AS.J+DT*(SEL.JK-RML.JK)
        N   $AS=SEL
 3      R   SEL.KL=FIFZE($LO.K,$SDY.K,(FL.K+FOH.K))
 4      A   $LO.K=MIN($RSR.K,$HRN.K)
 5      L   $RSR.K=$RSR.J+DT*(TIN.JK-SEL.JK-TOU.JK)
        N   $RSR=INV
 6      A   $HRN.K=FIFGE(NS,(FOH.K-PRS.K),PRS.K,FDH.K)
 7      A   $SDY.K=MIN(($SELF.K*FL.K),$HRN.K)
 8      A   $SELF.K=TABHL(TSLF,$CV.K,.4,1,.2)
 9      A   $CV.K=$RSR.K/PSTV($EQ.K)
10      A   $EQ.K=FL.K*(UNTY(HAG-AGE))
11      R   TOU.KL=$SUR.K/DLY
12      A   $SUR.K=ZERO($RSR.K-$EQ.K)
13      A   HBTOB.K=PSTV($RSR.K+$AS.K)
14      A   VRM.K=RML.JK*$VU*YST*$SOF.K
        N   $VU=TABHL(TTYI,$AHA,0,320,10)
        N   $AHA=DRT+(MAX(HAG,AGE))
15      A   $SOF.K=TABHL(TOFM,SOH.K,0,3,.5)
16      A   SOH.K=MIN(SO.K,RML.JK)
17      A   NC.K=RML.K/PSTV(SOH.K)
        MEND
        T   TSLF=0/.3/.6/1
        T   TOFM=.5/.8/.9/.93/.95/.98/1
        C   NS=0/DRT=2
        NOTE
        NOTE  STATE OF A FOREST TYPE (OBTAH)
        MACRO OBTAH(IA,IB,IC,ID,IE,IF,IG,CA,CB,CC,CD,CE,CF,CG,
        X   DA,DB,DC,DD,DE,DF,DG,HA,HB,HC,HD,HE,HF,HG,FA,FB,FC,FD,FE,FF,FG,
        X   TTYI,YST,TMR,ISC,ISC,
        X   SA,SB,SC,SD,SE,SF,SG,PTI,VT,TNH,WCH,A,B,C,D,E,F,G)
 1      L   OBTAH.K=OBTAH.J+DT*($CON.JK-$REV.JK)
        N   OBTAH=IA+IB+IC+ID+IE+IF+IG
 2      R   $CON.KL=CA.K+CB.K+CC.K+CD.K+CE.K+CF.K+CG.K
 3      R   $REV.KL=$RVA.K+$RVB.K+$RVC.K+$RVD.K+$RVE.K+$RVF.K+$RVG.K
 4      A   $RVA.K=ZERO(NS)
 5      A   $RVB.K=ZERO(NS)
 6      A   $RVC.K=ZERO(NS)
```

```
  7     A   $RVD.K=ZERO(NS)
  8     A   $RVE.K=ZERO(NS)
  9     A   $RVF.K=ZERO(NS)
 10     A   $RVG.K=ZERO(NS)
 11     A   A.K=HBTOB($TA.JK,$SBO.K,$FLA.K,$FBO.K,$FAO.K,IA,DA,$AA,HA,
        X   TTYI,YST,$SO.K,$TOA.JK,SA.JK,$RA.JK,$VA.K,$SCA.K,$NOA.K)
 12     A   B.K=HBTOB($TB.JK,$SCC.K,$FLB.K,$FCC.K,$FAC.K,IB,CB,$AB,HB,
        X   TTYI,YST,$SO.K,$TOB.JK,SB.JK,$RB.JK,$VB.K,$SCB.K,$NOB.K)
 13     A   C.K=HBTOB($TC.JK,$SDC.K,$FLC.K,$FDC.K,$FAC.K,IC,DC,$AC,HC,
        X   TTYI,YST,$SO.K,$TOC.JK,SC.JK,$RC.JK,$VC.K,$SCC.K,$NOC.K)
 14     A   C.K=HBTCB($TD.JK,$SEC.K,$FLD.K,$FEO.K,$FAC.K,ID,DD,$AD,HD,
        X   TTYI,YST,$SO.K,$TCD.JK,SC.JK,$RD.JK,$VD.K,$SCD.K,$NOD.K)
 15     A   E.K=HBTOB($TE.JK,$SFC.K,$FLE.K,$FFO.K,$FAC.K,IE,DE,$AE,HE,
        X   TTYI,YST,$SO.K,$TOE.JK,SE.JK,$RE.JK,$VE.K,$SCE.K,$NOE.K)
 16     A   F.K=HBTOB($TF.JK,SG.JK,$FLF.K,$FLG.K,$FAC.K,IF,CF,$AF,HF,
        X   TTYI,YST,$SO.K,$TOF.JK,SF.JK,$RF.JK,$VF.K,$SCF.K,$NOF.K)
 17     A   G.K=HBTCB($TG.JK,NS,$FLG.K,NS,$FAC.K,IG,CG,$AG,HG,
        X   TTYI,YST,$SO.K,$TOG.JK,SG.JK,$RG.JK,$VG.K,$SCG.K,$NOG.K)
 18     R   $TA.KL=ZERO($R.K+$TCG.K+CA.K-$RVG.K)
 19     A   $R.K=$RA.JK+$RB.JK+$RC.JK+$RD.JK+$RE.JK+$RF.JK+$RG.JK
 20     R   $TB.KL=ZERO($TCA.JK+CB.K-$RVA.K)
 21     R   $TC.KL=ZERO($TCB.JK+CC.K-$RVB.K)
 22     R   $TD.KL=ZERO($TCC.JK+CD.K-$RVC.K)
 23     R   $TE.KL=ZERO($TCD.JK+CE.K-$RVD.K)
 24     R   $TF.KL=ZERO($TCE.JK+CF.K-$RVE.K)
 25     R   $TG.KL=ZERO($TCF.JK+CG.K-$RVF.K)
 26     A   $SBC.K=SB.JK+$SCC.K
 27     A   $SCC.K=SC.JK+$SDC.K
 28     A   $SDO.K=SD.JK+$SEC.K
 29     A   $SEC.K=SE.JK+$SFC.K
 30     A   $SFO.K=SF.JK+SG.JK
 31     A   $FLA.K=(CBTAH.K*FA)/(MAX($AA,HA))
 32     A   $FLB.K=(CBTAH.K*FB)/(MAX($AB,HB))
 33     A   $FLC.K=(OBTAH.K*FC)/(MAX($AC,HC))
 34     A   $FLD.K=(CBTAH.K*FD)/(MAX($AD,HD))
 35     A   $FLE.K=(CBTAH.K*FE)/(MAX($AE,HE))
 36     A   $FLG.K=(CBTAH.K*FG)/(MAX($AG,HG))
 37     A   $FLF.K=(CBTAH.K*FF)/(MAX($AF,HF))
 38     A   $FAC.K=$FLA.K+$FEO.K
 39     A   $FBC.K=$FLB.K+$FCO.K
 40     A   $FCO.K=$FLC.K+$FCC.K
 41     A   $FDC.K=$FLD.K+$FEC.K
 42     A   $FEC.K=$FLE.K+$FFO.K
 43     A   $FFC.K=$FLF.K+$FLG.K
        N   $AA=1
        N   $AB=CA+1
        N   $AC=DA+DB+1
        N   $AD=CA+DB+DC+1
        N   $AE=CA+DB+DC+DC+1
        N   $AF=DA+DB+DC+DD+CE+1
        N   $AG=CA+DB+DC+CC+CE+CF+1
 44     A   $SC.K=NORMRN(ISO,ISC)
 45     A   PTI.K=VT.K/$TIM.K
 46     A   VT.K=$VA.K+$VB.K+$VC.K+$VD.K+$VE.K+$VF.K+$VG.K
 47     A   $TIM.K=(CBTAH.K/TMR)*$TYI*YST
        N   $TYI=TABHL(TTYI,TMR,0,320,10)
 48     A   TNF.K=$NCA.K+$NOE.K+$NOC.K+$NCD.K+$NCE.K+$NCF.K+$NOG.K
 49     A   WOH.K=$OA.K+$CB.K+$CC.K+$CD.K+$CE.K+$CF.K+$CG.K
```

```
50     A   $CA.K=($RA.K/($R.K+1E-6))*$SCA.K
51     A   $OB.K=($RB.K/($R.K+1E-6))*$SCB.K
52     A   $CC.K=($RC.K/($R.K+1E-6))*$SCC.K
53     A   $OD.K=($RD.K/($R.K+1E-6))*$SCD.K
54     A   $CE.K=($RE.K/($R.K+1E-6))*$SCE.K
55     A   $CF.K=($RF.K/($R.K+1E-6))*$SCF.K
56     A   $OG.K=($RG.K/($R.K+1E-6))*$SOG.K
       MEND
       NCTE
       NCTE   FCREST TYPE SECTOR
 2     A   BIVY.K=OBTAH(ISE.ISA.IP6.IP8.IP1.IMT.ICG,CSE,CSA,CP6,CP8,CP1,CMT,COG,
       X   DSE,DSA,DP6,DP8,DP1,DMT,DCG,HSE,HSA,HP6,HP8,HP1,HMT,HCG,
       X   SEF,SAF,P6F,P8F,P1F,MTF,CGF,TTYI,YST,TMR,
       X   ISC,ISD,SES.K,SAS.K,P6S.K,P8S.K,P1S.K,MTS.K,CGS.K,PTI.K,VT.K,NOP.K,
       X   CPS.K,SED.K,SAP.K,P6.K,P8.K,P1.K,MT.K,CG.K)
 3     A   CSE.K=ZERC(NS)
 4     A   CSA.K=ZERO(NS)
 5     A   CP6.K=ZERO(NS)
 6     A   CP8.K=ZERC(NS)
 7     A   CP1.K=ZERC(NS)
 8     A   CMT.K=ZERC(NS)
 9     A   CCG.K=ZERC(NS)
       C   ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1808/IMT=366/IOG=185   B.IVY.ST
       C   DSE=5/DSA=30/DP6=15/DP8=15/DP1=20/DMT=35/DOG=180
       T   TTYI=0/.23/.41/.6/.81/1/1.18/1.33/1.47/1.61/1.75/1.85/1.89/1.92/1.94/
       X   1.96/1.97/1.98/1.99/2/2.01/2.02/2.02/2.03/2.04/2.04/2.05/2.06/2.06/
       X   2.07/2.08/2.08/2.09
       C   YST=2520
       C   TMR=50
       NCTE
       NOTE   SUPPLEMENTARY INFCRMATICN
10     A   PSE.K=SED.K/BIVY.K
11     A   PSA.K=SAP.K/BIVY.K
12     A   PP6.K=P6.K/BIVY.K
13     A   PP8.K=P8.K/BIVY.K
14     A   PP1.K=P1.K/BIVY.K
15     A   PMT.K=MT.K/BIVY.K
16     A   PCG.K=CG.K/BIVY.K
17     A   PSEA.K=(SED.K+SAP.K)/BIVY.K
18     A   PO8M.K=(P8.K+P1.K+MT.K)/BIVY.K
19     A   P1M.K=(P1.K+MT.K)/BIVY.K
20     A   PMC.K=(MT.K+CG.K)/BIVY.K
21     A   CPM.K=NOP.K/(BIVY.K/640)
       NCTE
       NOTE   BENEFIT INFCRMATICN
22     A   SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)
       T   TSEMT=0/.3/.6/.8/.9/1
23     A   UGL.K=UGS.K*UGN.K*UGC.K
24     A   UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)
       T   TUGS=0/.1/.2/.3/.5/.7/1
25     A   UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)
       T   TUGN=1/.9/.7/.4/.01
26     A   UGO.K=TABHL(TUGO,OPS.K,0,30,3)
       T   TUGO=0/.50/.65/.70/.75/.80/.85/.90/.95/.97/1
27     A   VIS.K=VSE.K*VBAL.K*VPCG.K
28     A   VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)
       T   TVSE=.2/.6/.9/1/.9/.6/.2
29     A   VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)
```

```
         T    TVBA=.4/.7/1/.7/.4
 30      A    BAL.K=(P8.K+P1.K+MT.K)/(SEC.K+SAF.K+P6.K)
 31      A    VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)
         T    TVPO=.4/.7/.9/1/.9/.8/.6/.4
 32      A    DEER.K=HTD.K*CTD.K*DMA.K
 33      A    HTD.K=TABHL(THTD,PSE.K,0,.07,.01)
         T    THTD=0/.1/.2/.5/.7/.8/.9/1
 34      A    CTD.K=TABHL(TCTD,CPS.K,0,60,6)
         T    TCTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45
 35      A    DMA.K=TABHL(TDMA,P1M.K,0,.2,.05)
         T    TDMA=.1/.2/.5/.8/1
 36      A    SQU.K=THS.K*SDT.K
 37      A    THS.K=TABHL(TTHS,PC8M.K,0,.4,.1)
         T    TTHS=0/.2/.4/.8/1
 38      A    SDT.K=TABHL(TSDT,POG.K,0,.3,.1)
         T    TSDT=.1/.7/.8/1
 39      A    TUR.K=TURT.K*TURC.K
 40      A    TURT.K=TABHL(TTRT,PC8M.K,0,.5,.1)
         T    TTRT=0/.1/.2/.5/.8/1
 41      A    TURC.K=TABHL(TTRC,OPS.K,0,28,2)
         T    TTRC=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4
 42      A    GRS.K=GRH.K*GRC.K
 43      A    GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)
         T    TGRH=0/.2/.7/.9/1
 44      A    GRC.K=TABHL(TGRO,OPS.K,0,60,6)
         T    TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5
 45      A    BEAR.K=BDT.K*BSMT.K*BHMT.K
 46      A    BDT.K=TABHL(TBDT,POG.K,0,.3,.1)
         T    TBDT=.2/.8/.9/1
 47      A    BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)
         T    TBSM=0/.5/1
 48      A    BHMT.K=TABHL(TBHM,PC8M.K,0,.4,.1)
         T    TBHM=0/.2/.4/.8/1
 49      A    PIL.K=TABHL(TPIL,POG.K,0,.6,.1)
         T    TPIL=.1/.4/.6/.8/.9/.95/1
 50      A    HAR.K=TABHL(THAR,PMO.K,0,.5,.05)
         T    THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1
 51      A    DCN.K=TABHL(TDCN,P1M.K,0,.4,.05)
         T    TDCN=.1/.15/.3/.4/.6/.8/.9/.95/1
 52      A    FLIC.K=FLF.K*FLN.K*FLC.K
 53      A    FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)
         T    TFLF=.05/.15/.3/.5/.7/.9/1
 54      A    FLN.K=TABHL(TFLN,PMC.K,0,.2,.05)
         T    TFLN=.5/.8/.9/.95/1
 55      A    FLC.K=TABHL(TFLO,OPS.K,0,10,2)
         T    TFLO=.05/.1/.5/.9/.95/1
 56      A    BLU.K=BBH.K*BBO.K
 57      A    BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)
         T    TBBH=0/.1/.2/.4/.7/.9/1
 58      A    BBO.K=TABHL(TBBO,CPS.K,0,60,6)
         T    TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7
 59      A    OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)
         T    TOVN=.1/.2/.4/.7/.8/.9/1
 60      A    TWE.K=TWH.K*TWC.K
 61      A    TWH.K=TABHL(TTWE,PSA.K,0,.45,.05)
         T    TTWE=0/.1/.2/.4/.6/.8/.85/.9/.95/1
 62      A    TWC.K=TABHL(TTWC,OPS.K,0,5,1)
         T    TTWC=.1/.5/.7/.8/.9/1
```

```
63      A   PWE.K=TABHL(TPWE,PMO.K,0,.7,.1)
        T   TPWE=.1/.2/.4/.7/.8/.9/.95/1
64      A   CQ.K=(TQ.K+NHQ)/NHQ
        N   NHQ=LOGN(NH)
        C   NH=7
65      A   TQ.K=(SEQ.K+SAQ.K+P6Q.K+P8Q.K+P1Q.K+MTQ.K+OGQ.K)
66      A   SEQ.K=PSE.K*LOGN(PSE.K)
67      A   SAQ.K=PSA.K*LOGN(PSA.K)
68      A   P6Q.K=PP6.K*LOGN(PP6.K)
69      A   P8Q.K=PP8.K*LOGN(PP8.K)
70      A   P1Q.K=PP1.K*LOGN(PP1.K)
71      A   MTQ.K=PMT.K*LOGN(PMT.K)
72      A   OGQ.K=POG.K*LOGN(POG.K)
73      A   WYI.K=WY.K/(BIVY.K*MSWI)
        C   MSWI=.417
74      A   WY.K=(SEWI*SED.K)+(SAWI*SAP.K)
        N   SEWI=SEW/DSE
        N   SEW=TABHL(TWY,DSE,1,10,1)
        T   TWY=.98/1.72/2.33/2.84/3.28/3.65/3.97/4.24/4.48/4.68
        N   SAWI=(SAWM-SEW)/DSA
        C   SAWM=5.3
        NOTE
        NOTE   PROGRAM CONTROLS SECTOR
        SPEC   DT=.25/LENGTH=170
75      A   PRTPER.K=1+STEP(39,11)
        PRINT 1)SED,SES/2)SAP,SAS/3)P6,P6S/4)P8,P8S/5)P1,P1S/6)MT,MTS/7)OG,OGS/
        PRINT 8)PTI,VT/9)PSE,PSA/10)PP6,POG/11)PSEA,PC8M/12)P1M,PMO/
        PRINT 13)BAL,OPM/14)CPS,WY
76      A   PLTPER.K=1+STEP(3,11)
        PLOT   PSE=S(0,.4)/PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,POG=O(0,.8)
        PLOT   PTI=T,SEMT=I,BEAR=E,GRS=G,TUR=K,BLU=L,DEER=D,SQU=Q,WYI=#(0,1)
        PLOT   PTI=T,SEMT=I,DEER=D,SQU=Q,BLU=L(0,1)
        PLOT   VIS=V,UGL=U,OVN=O,FIL=P,FLIC=F,DON=N,TWE=W,PWE=E,HAR=H,CQ=*(0,1)
        NOTE
        NOTE   ANALYTIC SILVICULTURE CONTROLS
        C   HSE=0/HSA=0/HP6=0/HP8=0/HP1=0/HMT=0/HOG=0/ISC=0/ISD=0              WILDERN
        C   SEF=0/SAF=0/P6F=0/P8F=0/P1F=0/MTF=0/OGF=0                          WILDERN
        RUN    OPTIMUM WILDERNESS
```

APPENDIX B

EQUATIONS WITH DEFINITIONS OF THE ASSOCIATED VARIABLES

```
  MAINTAIN A POSITIVE VALUE

MACRO PSTV(X)                                                .4
    PSTV    - FUNCTION ENSURES A POSITIVE VALUE
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

PSTV.K=MAX(X.K,1E-6)                                         1, A
    PSTV    - FUNCTION ENSURES A POSITIVE VALUE
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

MEND

  MAINTAIN A VALUE EQUAL TO OR GREATER THAN UNITY

MACRO    UNTY(X)                                             .1
    UNTY    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ONE
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

UNTY.K=MAX(X.K,1)                                            1, A
    UNTY    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ONE
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

MEND

  MAINTAIN A VALUE EQUAL TO OR GREATER THAN ZERO

MACRO    ZERO(X)                                             .1
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

ZERO.K=MAX(X.K,0)                                            1, A
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    X       - VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                UNTY,ZERO

MEND
```

STATE OF A HABITAT TYPE (HBTOB)

```
MACRO    HBTOB(TIN,PRS,FL,FOH,FDH,INV,DLY,AGE,HAG,   .1
  TTYI,YST,SO,TOU,SEL,RML,VRM,SOH,NO)
    HBTOB   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                HABITAT (AREA)
    TIN     - AREA TRANSFERRED INTO A HABITAT (AREA)
    PRS     - PREVIOUS SALES FROM ALL OLDER HABITATS
                (AREA)
    FL      - FLOW OF A SPECIFIED HABITAT (AREA/YEAR)
    FOH     - FLOW OF ALL HABITATS OLDER THAN THE
                SPECIFIED (AREA/YEAR)
    FDH     - FLOW OF ALL DIVERTED HABITATS (AREA/YEAR)
    INV     - INITIAL INVENTORY OF A SPECIFIED HABITAT
                (AREA)
    DLY     - DELAY IN FLOW,SUCCESSION,FOR A SPECIFIED
                HABITAT (YEARS)
    AGE     - YOUNGEST AGE OF A SPECIFIED HABITAT (YEARS)
    HAG     - HARVEST AGE DESIRED FOR A HABITAT (YEARS)
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    SO      - SIZE OF OPENING (AREA)
    TOU     - TRANSFER OUT OF A HABITAT BY SUCCESSION
                (AREA/YEAR)
    SEL     - AMOUNT OF A HABITAT TO SELL (AREA)
    RML     - AMOUNT OF A HABITAT REMOVED BY HARVEST
                (AREA)
    VRM     - VOLUME OF TIMBER REMOVED BY HARVEST
                (VOLUME/YEAR)
    SOH     - SIZE OF OPENING FOR PARTICULAR HABITAT
                (AREA)
    NO      - NUMBER OF OPENINGS FOR A PARTICULAR HABITAT
                (AREA)

RML.KL=($AS.K/DRT)                                   1, R
    RML     - AMOUNT OF A HABITAT REMOVED BY HARVEST
                (AREA)
    $AS     - ACCUMULATED SALES FOR A HABITAT (AREA)
    DRT     - DELAY FOR SALE AND REMOVAL OF TIMBER
                (YEARS)

$AS.K=$AS.J+DT*(SEL.JK-RML.JK)                       2, L
$AS=SEL                                              2.1, N
    $AS     - ACCUMULATED SALES FOR A HABITAT (AREA)
    DT      - COMPUTATION INTERVAL (YEARS)
    SEL     - AMOUNT OF A HABITAT TO SELL (AREA)
    RML     - AMOUNT OF A HABITAT REMOVED BY HARVEST
                (AREA)
```

```
SEL.KL=FIFZE($LQ.K,$SDY.K,(FL.K+FOH.K))                      3, R
    SEL     - AMOUNT OF A HABITAT TO SELL (AREA)
    FIFZE   - FUNCTION,SELECTS FIRST IF THIRD EQUALS ZERO
    $LQ     - LIQUIDATE RESERVES OF A HABITAT (AREA/YEAR)
    $SDY    - STEADY STATE SALES OF A HABITAT (AREA/YEAR)
    FL      - FLOW OF A SPECIFIED HABITAT (AREA/YEAR)
    FOH     - FLOW OF ALL HABITATS OLDER THAN THE
                SPECIFIED (AREA/YEAR)

$LQ.K=MIN($RSR.K,$HRN.K)                                     4, A
    $LQ     - LIQUIDATE RESERVES OF A HABITAT (AREA/YEAR)
    MIN     - FUNCTION,SELECTS MINIMUM VALUE
    $RSR    - RESERVE ACCUMULATION FOR A HABITAT (AREA)
    $HRN    - HARVEST REQUIRED FROM A HABITAT (AREA/YEAR)

$RSR.K=$RSR.J+DT*(TIN.JK-SEL.JK-TOU.JK)                      5, L
$RSR=INV                                                     5.1.
    $RSR    - RESERVE ACCUMULATION FOR A HABITAT (AREA)
    DT      - COMPUTATION INTERVAL (YEARS)
    TIN     - AREA TRANSFERRED INTO A HABITAT (AREA)
    SEL     - AMOUNT OF A HABITAT TO SELL (AREA)
    TOU     - TRANSFER OUT OF A HABITAT BY SUCCESSION
                (AREA/YEAR)
    INV     - INITIAL INVENTORY OF A SPECIFIED HABITAT
                (AREA)

$HRN.K=FIFGE(NS,(FDH.K-PRS.K),PRS.K,FDH.K)                   6, A
    $HRN    - HARVEST REQUIRED FROM A HABITAT (AREA/YEAR)
    FIFGE   - FUNCTION,SELECTS FIRST IF THIRD EQUALS,
                EXCEEDS THE FOURTH
    NS      - NULL STANDARD,EQUALS ZERO
    FDH     - FLOW OF ALL DIVERTED HABITATS (AREA/YEAR)
    PRS     - PREVIOUS SALES FROM ALL OLDER HABITATS
                (AREA)

$SDY.K=MIN(($SELF.K*FL.K),$HRN.K)                            7, A
    $SDY    - STEADY STATE SALES OF A HABITAT (AREA/YEAR)
    MIN     - FUNCTION,SELECTS MINIMUM VALUE
    $SELF   - SELL FRACTION (DIMENSIONLESS)
    FL      - FLOW OF A SPECIFIED HABITAT (AREA/YEAR)
    $HRN    - HARVEST REQUIRED FROM A HABITAT (AREA/YEAR)

$SELF.K=TABHL(TSLF,$CV.K,.4,1,.2)                            8, A
    $SELF   - SELL FRACTION (DIMENSIONLESS)
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TSLF    - TABLE FOR SELL FRACTIONS (DIMENSIONLESS)
    $CV     - COVERAGE OF RESERVES FOR A HABITAT
                (DIMENSIONLESS)

$CV.K=$RSR.K/PSTV($EQ.K)                                     9, A
    $CV     - COVERAGE OF RESERVES FOR A HABITAT
                (DIMENSIONLESS)
    $RSR    - RESERVE ACCUMULATION FOR A HABITAT (AREA)
    PSTV    - FUNCTION ENSURES A POSITIVE VALUE
    $EQ     - EQUILIBRIUM RESERVES FOR SALES (AREA)
```

```
$EQ.K=FL.K*(UNTY(HAG-AGE))                                 10. A
    $EQ     - EQUILIBRIUM RESERVES FOR SALES (AREA)
    FL      - FLOW OF A SPECIFIED HABITAT (AREA/YEAR)
    UNTY    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ONE
    HAG     - HARVEST AGE DESIRED FOR A HABITAT (YEARS)
    AGE     - YOUNGEST AGE OF A SPECIFIED HABITAT (YEARS)

TOU.KL=$SUR.K/DLY                                          11. R
    TOU     - TRANSFER OUT OF A HABITAT BY SUCCESSION
                (AREA/YEAR)
    $SUR    - SUCCESSION RESERVES (AREA)
    DLY     - DELAY IN FLOW,SUCCESSION,FOR A SPECIFIED
                HABITAT (YEARS)

$SUR.K=ZERO($RSR.K-$EQ.K)                                  12. A
    $SUR    - SUCCESSION RESERVES (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    $RSR    - RESERVE ACCUMULATION FOR A HABITAT (AREA)
    $EQ     - EQUILIBRIUM RESERVES FOR SALES (AREA)

HBTOB.K=PSTV($RSR.K+$AS.K)                                 13. A
    HBTOB   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                HABITAT (AREA)
    PSTV    - FUNCTION ENSURES A POSITIVE VALUE
    $RSR    - RESERVE ACCUMULATION FOR A HABITAT (AREA)
    $AS     - ACCUMULATED SALES FOR A HABITAT (AREA)

VRM.K=RML.JK*$VU*YST*$SOF.K                                14. A
$VU=TABHL(TTYI,$AHA,0,320,10)                              14.1, N
$AHA=DRT+(MAX(HAG,AGE))                                    14.2, N
    VRM     - VOLUME OF TIMBER REMOVED BY HARVEST
                (VOLUME/YEAR)
    RML     - AMOUNT OF A HABITAT REMOVED BY HARVEST
                (AREA)
    $VU     - VOLUME FACTOR FOR TIMBER (VOLUME UNITS/UNIT
                AREA)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    $SOF    - SIZE OF OPENING FACTOR (DIMENSIONLESS)
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)
    $AHA    - ACTUAL HARVEST AGE (YEARS)
    DRT     - DELAY FOR SALE AND REMOVAL OF TIMBER
                (YEARS)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    HAG     - HARVEST AGE DESIRED FOR A HABITAT (YEARS)
    AGE     - YOUNGEST AGE OF A SPECIFIED HABITAT (YEARS)
```

```
$SOF.K=TABHL(TOFM,SOH.K,0,3,.5)                                 15, A
     $SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)
     TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
     TOFM     - TABLE FOR OPENING FACTOR MODIFICATION
                  (DIMENSIONLESS)
     SOH      - SIZE OF OPENING FOR PARTICULAR HABITAT
                  (AREA)

SOH.K=MIN(SO.K,RML.JK)                                          16, A
     SOH      - SIZE OF OPENING FOR PARTICULAR HABITAT
                  (AREA)
     MIN      - FUNCTION,SELECTS MINIMUM VALUE
     SO       - SIZE OF OPENING (AREA)
     RML      - AMOUNT OF A HABITAT REMOVED BY HARVEST
                  (AREA)

NO.K=RML.K/PSTV(SOH.K)                                          17, A
     NO       - NUMBER OF OPENINGS FOR A PARTICULAR HABITAT
                  (AREA)
     RML      - AMOUNT OF A HABITAT REMOVED BY HARVEST
                  (AREA)
     PSTV     - FUNCTION ENSURES A POSITIVE VALUE
     SOH      - SIZE OF OPENING FOR PARTICULAR HABITAT
                  (AREA)

MEND

TSLF=0/.3/.6/1                                                  1, T
TOFM=.5/.8/.9/.93/.95/.98/1                                     1.1, T
NS=0/DRT=2                                                      1.2, C
     TSLF     - TABLE FOR SELL FRACTIONS (DIMENSIONLESS)
     TOFM     - TABLE FOR OPENING FACTOR MODIFICATION
                  (DIMENSIONLESS)
     NS       - NULL STANDARD,EQUALS ZERO
     DRT      - DELAY FOR SALE AND REMOVAL OF TIMBER
                  (YEARS)
```

```
 STATE OF A FOREST TYPE (OBTAH)

MACRO     OBTAH(IA,IB,IC,ID,IE,IF,IG,CA,CB,CC,CD,CE,  .1
 CF,CG,DA,DB,DC,DD,DE,DF,DG,HA,HB,HC,HD,HE,HF,HG,
 FA,FB,FC,FD,FE,FF,FG,TTYI,YST,TMR,ISO,ISD,SA,SB,
 SC,SD,SE,SF,SG,PTI,VT,TNH,WOH,A,B,C,D,E,F,G)
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    IA      - INITIAL AREA FOR HABITAT 'A' (AREA)
    IB      - INITIAL AREA FOR HABITAT 'B' (AREA)
    IC      - INITIAL AREA FOR HABITAT 'C' (AREA)
    ID      - INITIAL AREA FOR HABITAT 'D' (AREA)
    IE      - INITIAL AREA FOR HABITAT 'E' (AREA)
    IF      - INITIAL AREA FOR HABITAT 'F' (AREA)
    IG      - INITIAL AREA FOR HABITAT 'G' (AREA)
    CA      - CONVERSION OF LAND TO HABITAT 'A' (AREA)
    CB      - CONVERSION OF LAND TO HABITAT 'B' (AREA)
    CC      - CONVERSION OF LAND TO HABITAT 'C' (AREA)
    CD      - CONVERSION OF LAND TO HABITAT 'D' (AREA)
    CE      - CONVERSION OF LAND TO HABITAT 'E' (AREA)
    CF      - CONVERSION OF LAND TO HABITAT 'F' (AREA)
    CG      - CONVERSION OF LAND TO HABITAT 'G' (AREA)
    DA      - DELAY FOR HABITAT 'A' (YEARS)
    DB      - DELAY FOR HABITAT 'B' (YEARS)
    DC      - DELAY FOR HABITAT 'C' (YEARS)
    DD      - DELAY FOR HABITAT 'D' (YEARS)
    DE      - DELAY FOR HABITAT 'E' (YEARS)
    DF      - DELAY FOR HABITAT 'F' (YEARS)
    DG      - DELAY FOR HABITAT 'G' (YEARS)
    HA      - HARVEST AGE DESIRED FOR HABITAT 'A' (YEARS)
    HB      - HARVEST AGE DESIRED FOR HABITAT 'B' (YEARS)
    HC      - HARVEST AGE DESIRED FOR HABITAT 'C' (YEARS)
    HD      - HARVEST AGE DESIRED FOR HABITAT 'D' (YEARS)
    HE      - HARVEST AGE DESIRED FOR HABITAT 'E' (YEARS)
    HF      - HARVEST AGE DESIRED FOR HABITAT 'F' (YEARS)
    HG      - HARVEST AGE DESIRED FOR HABITAT 'G' (YEARS)
    FA      - FRACTION OF TYPE DIVERTED FROM HABITAT 'A'
                (PERCENT)
    FB      - FRACTION OF TYPE DIVERTED FROM HABITAT 'B'
                (PERCENT)
    FC      - FRACTION OF TYPE DIVERTED FROM HABITAT 'C'
                (PERCENT)
    FD      - FRACTION OF TYPE DIVERTED FROM HABITAT 'D'
                (PERCENT)
    FE      - FRACTION OF TYPE DIVERTED FROM HABITAT 'E'
                (PERCENT)
    FF      - FRACTION OF TYPE DIVERTED FROM HABITAT 'F'
                (PERCENT)
    FG      - FRACTION OF TYPE DIVERTED FROM HABITAT 'G'
                (PERCENT)
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    TMR     - TIMBER ROTATION FOR MAXIMUM YIELD (YEARS)
    ISO     - INITIAL SIZE OF OPENINGS (AREA)
    ISD     - INITIAL STANDARD DEVIATION OF SIZE OF
                OPENINGS (AREA)
```

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     SA       - AMOUNT OF HABITAT 'A' TO SELL (AREA)
     SB       - AMOUNT OF HABITAT 'B' TO SELL (AREA)
     SC       - AMOUNT OF HABITAT 'C' TO SELL (AREA)
     SD       - AMOUNT OF HABITAT 'D' TO SELL (AREA)
     SE       - AMOUNT OF HABITAT 'E' TO SELL (AREA)
     SF       - AMOUNT OF HABITAT 'F' TO SELL (AREA)
     SG       - AMOUNT OF HABITAT 'G' TO SELL (AREA)
     PTI      - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
     VT       - TOTAL VOLUME OF TIMBER REMOVED FROM A
                  FOREST TYPE (VOLUME)
     TNH      - TOTAL NUMBER OF OPENINGS FOR A TYPE
     WOH      - WEIGHTED OPENING SIZE FOR A TYPE
     A        - AREA FOR HABITAT 'A' (AREA)
     B        - AREA FOR HABITAT 'B' (AREA)
     C        - AREA FOR HABITAT 'C' (AREA)
     D        - AREA FOR HABITAT 'D' (AREA)
     E        - AREA FOR HABITAT 'E' (AREA)
     F        - AREA FOR HABITAT 'F' (AREA)
     G        - AREA FOR HABITAT 'G' (AREA)

OBTAH.K=OBTAH.J+DT*($CON.JK-$REV.JK)                        1. L
OBTAH=IA+IB+IC+ID+IE+IF+IG                                  1.1.
     OBTAH    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                  FOREST TYPE(AREA)
     DT       - COMPUTATION INTERVAL (YEARS)
     $CON     - AMOUNT OF LAND CONVERTED TO A FOREST TYPE
     $REV     - REVERSION OF LAND FROM A TYPE OF HABITAT
                  (AREA)
     IA       - INITIAL AREA FOR HABITAT 'A' (AREA)
     IB       - INITIAL AREA FOR HABITAT 'B' (AREA)
     IC       - INITIAL AREA FOR HABITAT 'C' (AREA)
     ID       - INITIAL AREA FOR HABITAT 'D' (AREA)
     IE       - INITIAL AREA FOR HABITAT 'E' (AREA)
     IF       - INITIAL AREA FOR HABITAT 'F' (AREA)
     IG       - INITIAL AREA FOR HABITAT 'G' (AREA)

$CON.KL=CA.K+CB.K+CC.K+CD.K+CE.K+CF.K+CG.K                  2. R
     $CON     - AMOUNT OF LAND CONVERTED TO A FOREST TYPE
     CA       - CONVERSION OF LAND TO HABITAT 'A' (AREA)
     CB       - CONVERSION OF LAND TO HABITAT 'B' (AREA)
     CC       - CONVERSION OF LAND TO HABITAT 'C' (AREA)
     CD       - CONVERSION OF LAND TO HABITAT 'D' (AREA)
     CE       - CONVERSION OF LAND TO HABITAT 'E' (AREA)
     CF       - CONVERSION OF LAND TO HABITAT 'F' (AREA)
     CG       - CONVERSION OF LAND TO HABITAT 'G' (AREA)

$REV.KL=$RVA.K+$RVB.K+$RVC.K+$RVD.K+$RVE.K+$RVF.K+          3. R
  $RVG.K
     $REV     - REVERSION OF LAND FROM A TYPE OF HABITAT
                  (AREA)
     $RVA     - REVERSION OF LAND FROM HABITAT 'A' (AREA)
     $RVB     - REVERSION OF LAND FROM HABITAT 'B' (AREA)
     $RVC     - REVERSION OF LAND FROM HABITAT 'C' (AREA)
     $RVD     - REVERSION OF LAND FROM HABITAT 'D' (AREA)
     $RVE     - REVERSION OF LAND FROM HABITAT 'E' (AREA)
     $RVF     - REVERSION OF LAND FROM HABITAT 'F' (AREA)
     $RVG     - REVERSION OF LAND FROM HABITAT 'G' (AREA)
```

```
$RVA.K=ZERO(NS)                                            4, A
    $RVA    - REVERSION OF LAND FROM HABITAT 'A' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVB.K=ZERO(NS)                                            5, A
    $RVB    - REVERSION OF LAND FROM HABITAT 'B' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVC.K=ZERO(NS)                                            6, A
    $RVC    - REVERSION OF LAND FROM HABITAT 'C' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVD.K=ZERO(NS)                                            7, A
    $RVD    - REVERSION OF LAND FROM HABITAT 'D' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVE.K=ZERO(NS)                                            8, A
    $RVE    - REVERSION OF LAND FROM HABITAT 'E' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVF.K=ZERO(NS)                                            9, A
    $RVF    - REVERSION OF LAND FROM HABITAT 'F' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

$RVG.K=ZERO(NS)                                           10, A
    $RVG    - REVERSION OF LAND FROM HABITAT 'G' (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO
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A.K=HBTOB($TA.JK,$SBO.K,$FLA.K,$FBO.K,$FAO.K,IA,DA, 11, A
  $AA,HA,TTYI,YST,$SO.K,$TOA.JK,SA.JK,$RA.JK,$VA.K,
  $SOA.K,$NOA.K)
    A        - AREA FOR HABITAT 'A' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 HABITAT (AREA)
    $TA      - TRANSFER LAND TO HABITAT 'A' (AREA)
    $SBO     - SALE OF HABITAT 'B' AND OLDER (AREA
    $FLA     - FLOW OF HABITAT 'A' (AREA/YEAR)
    $FBO     - FLOW OF HABITAT 'B' AND OLDER (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IA       - INITIAL AREA FOR HABITAT 'A' (AREA)
    DA       - DELAY FOR HABITAT 'A' (YEARS)
    $AA      - YOUNGEST AGE OF HABITAT 'A' (YEARS)
    HA       - HARVEST AGE DESIRED FOR HABITAT 'A' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                 UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                 VOLUMF/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOA     - TRANSFER AREA OUT OF HABITAT 'A'
    SA       - AMOUNT OF HABITAT 'A' TO SELL (AREA)
    $RA      - AREA OF HABITAT 'A' REMOVED BY HARVEST
                 (AREA)
    $VA      - VOLUME OF TIMBER REMOVED FROM HABITAT 'A'
    $SCA     - SIZE OF OPENINGS FOR HABITAT 'A'
    $NOA     - NUMBER OF OPENINGS FOR HABITAT 'A'

B.K=HBTOB($TB.JK,$SCO.K,$FLB.K,$FCO.K,$FAO.K,IB,DB, 12, A
  $AB,HB,TTYI,YST,$SO.K,$TOB.JK,SB.JK,$RB.JK,$VB.K,
  $SOB.K,$NOB.K)
    B        - AREA FOR HABITAT 'B' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 HABITAT (AREA)
    $TB      - TRANSFER LAND TO HABITAT 'B' (AREA)
    $SCO     - SALE OF HABITAT 'C' AND OLDER (AREA
    $FLB     - FLOW OF HABITAT 'B' (AREA/YEAR)
    $FCO     - FLOW OF HABITAT 'C' AND OLDER (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IB       - INITIAL AREA FOR HABITAT 'B' (AREA)
    DB       - DELAY FOR HABITAT 'B' (YEARS)
    $AB      - YOUNGEST AGE OF HABITAT 'B' (YEARS)
    HB       - HARVEST AGE DESIRED FOR HABITAT 'B' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                 UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                 VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOB     - TRANSFER AREA OUT OF HABITAT 'B'
    SB       - AMOUNT OF HABITAT 'B' TO SELL (AREA)
    $RB      - AREA OF HABITAT 'B' REMOVED BY HARVEST
                 (AREA)
    $VB      - VOLUME OF TIMBER REMOVED FROM HABITAT 'B'
    $SCB     - SIZE OF OPENINGS FOR HABITAT 'B'
    $NOB     - NUMBER OF OPENINGS FOR HABITAT 'B'
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C.K=HBTOB($TC.JK,$SDO.K,$FLC.K,$FDO.K,$FAO.K,IC,DC, 13, A
  $AC,HC,TTYI,YST,$SO.K,$TOC.JK,SC.JK,$RC.JK,$VC.K,
  $SOC.K,$NOC.K)
    C        - AREA FOR HABITAT 'C' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 HABITAT (AREA)
    $TC      - TRANSFER LAND TO HABITAT 'C' (AREA)
    $SDO     - SALE OF HABITAT 'D' AND OLDER (AREA
    $FLC     - FLOW OF HABITAT 'C' (AREA/YEAR)
    $FDO     - FLOW OF HABITAT 'D' AND OLDER (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IC       - INITIAL AREA FOR HABITAT 'C' (AREA)
    DC       - DELAY FOR HABITAT 'C' (YEARS)
    $AC      - YOUNGEST AGE OF HABITAT 'C' (YEARS)
    HC       - HARVEST AGE DESIRED FOR HABITAT 'C' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                 UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                 VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TCC     - TRANSFER AREA OUT OF HABITAT 'C'
    SC       - AMOUNT OF HABITAT 'C' TO SELL (AREA)
    $RC      - AREA OF HABITAT 'C' REMOVED BY HARVEST
                 (AREA)
    $VC      - VOLUME OF TIMBER REMOVED FROM HABITAT 'C'
    $SOC     - SIZE OF OPENINGS FOR HABITAT 'C'
    $NOC     - NUMBER OF OPENINGS FOR HABITAT 'C'

D.K=HBTOB($TD.JK,$SEO.K,$FLD.K,$FEO.K,$FAO.K,ID,DD, 14, A
  $AD,HD,TTYI,YST,$SO.K,$TOD.JK,SD.JK,$RD.JK,$VD.K,
  $SOD.K,$NOD.K)
    D        - AREA FOR HABITAT 'D' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 HABITAT (AREA)
    $TD      - TRANSFER LAND TO HABITAT 'D' (AREA)
    $SEO     - SALE OF HABITAT 'E' AND OLDER (AREA
    $FLD     - FLOW OF HABITAT 'D' (AREA/YEAR)
    $FEO     - FLOW OF HABITAT 'E' AND OLDER (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    ID       - INITIAL AREA FOR HABITAT 'D' (AREA)
    DD       - DELAY FOR HABITAT 'D' (YEARS)
    $AD      - YOUNGEST AGE OF HABITAT 'D' (YEARS)
    HD       - HARVEST AGE DESIRED FOR HABITAT 'D' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                 UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                 VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOD     - TRANSFER AREA OUT OF HABITAT 'D'
    SD       - AMOUNT OF HABITAT 'D' TO SELL (AREA)
    $RD      - AREA OF HABITAT 'D' REMOVED BY HARVEST
                 (AREA)
    $VD      - VOLUME OF TIMBER REMOVED FROM HABITAT 'D'
    $SOD     - SIZE OF OPENINGS FOR HABITAT 'D'
    $NOD     - NUMBER OF OPENINGS FOR HABITAT 'D'
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E.K=HBTOB($TE.JK,$SFO.K,$FLE.K,$FFO.K,$FAO.K,IE.DE, 15, A
  $AE,HE,TTYI,YST,$SO.K,$TOE.JK,SE.JK,$RE.JK,$VE.K,
  $SOE.K,$NOE.K)
    E        - AREA FOR HABITAT 'E' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                  HABITAT (AREA)
    $TE      - TRANSFER LAND TO HABITAT 'E' (AREA)
    $SFO     - SALE OF HABITAT 'F' AND OLDER (AREA
    $FLE     - FLOW OF HABITAT 'E' (AREA/YEAR)
    $FFO     - FLOW OF HABITAT 'F' AND OLDER (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IE       - INITIAL AREA FOR HABITAT 'E' (AREA)
    DE       - DELAY FOR HABITAT 'E' (YEARS)
    $AE      - YOUNGEST AGE OF HABITAT 'E' (YEARS)
    HE       - HARVEST AGE DESIRED FOR HABITAT 'E' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                  UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                  VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOE     - TRANSFER AREA OUT OF HABITAT 'E'
    SE       - AMOUNT OF HABITAT 'E' TO SELL (AREA)
    $RE      - AREA OF HABITAT 'E' REMOVED BY HARVEST
                (AREA)
    $VE      - VOLUME OF TIMBER REMOVED FROM HABITAT 'E'
    $SOE     - SIZE OF OPENINGS FOR HABITAT 'E'
    $NOE     - NUMBER OF OPENINGS FOR HABITAT 'E'

F.K=HBTOB($TF.JK,SG.JK,$FLF.K,$FLG.K,$FAO.K,IF.DF,  16, A
  $AF,HF.TTYI,YST,$SO.K,$TOF.JK,SF.JK,$RF.JK,$VF.K,
  $SOF.K,$NOF.K)
    F        - AREA FOR HABITAT 'F' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                  HABITAT (AREA)
    $TF      - TRANSFER LAND TO HABITAT 'F' (AREA)
    SG       - AMOUNT OF HABITAT 'G' TO SELL (AREA)
    $FLF     - FLOW OF HABITAT 'F' (AREA/YEAR)
    $FLG     - FLOW OF HABITAT 'G' (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IF       - INITIAL AREA FOR HABITAT 'F' (AREA)
    DF       - DELAY FOR HABITAT 'F' (YEARS)
    $AF      - YOUNGEST AGE OF HABITAT 'F' (YEARS)
    HF       - HARVEST AGE DESIRED FOR HABITAT 'F' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                  UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                  VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOF     - TRANSFER AREA OUT OF HABITAT 'F'
    SF       - AMOUNT OF HABITAT 'F' TO SELL (AREA)
    $RF      - AREA OF HABITAT 'F' REMOVED BY HARVEST
                (AREA)
    $VF      - VOLUME OF TIMBER REMOVED FROM HABITAT 'F'
    $SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)
    $NOF     - NUMBER OF OPENINGS FOR HABITAT 'F'
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G.K=HBTOB($TG.JK,NS,$FLG.K,NS,$FAO.K,IG,DG,$AG,HG,   17, A
  TTYI,YST,$SO.K,$TOG.JK,SG.JK,$RG.JK,$VG.K,$SOG.K,
  $NOG.K)
    G        - AREA FOR HABITAT 'G' (AREA)
    HBTOB    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 HABITAT (AREA)
    $TG      - TRANSFER LAND TO HABITAT 'G' (AREA)
    NS       - NULL STANDARD,EQUALS ZERO
    $FLG     - FLOW OF HABITAT 'G' (AREA/YEAR)
    $FAO     - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    IG       - INITIAL AREA FOR HABITAT 'G' (AREA)
    DG       - DELAY FOR HABITAT 'G' (YEARS)
    $AG      - YOUNGEST AGE OF HABITAT 'G' (YEARS)
    HG       - HARVEST AGE DESIRED FOR HABITAT 'G' (YEARS)
    TTYI     - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                 UNITS/UNIT AREA)
    YST      - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                 VOLUME/ACRE)
    $SO      - SIZE OF OPENING (AREA)
    $TOG     - TRANSFER AREA OUT OF HABITAT 'G'
    SG       - AMOUNT OF HABITAT 'G' TO SELL (AREA)
    $RG      - AREA OF HABITAT 'G' REMOVED BY HARVEST
                 (AREA)
    $VG      - VOLUME OF TIMBER REMOVED FROM HABITAT 'G'
    $SOG     - SIZE OF OPENINGS FOR HABITAT 'G'
    $NOG     - NUMBER OF OPENINGS FOR HABITAT 'G'

$TA.KL=ZERO($R.K+$TOG.K+CA.K-$RVG.K)                 18, R
    $TA      - TRANSFER LAND TO HABITAT 'A' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $TOG     - TRANSFER AREA OUT OF HABITAT 'G'
    CA       - CONVERSION OF LAND TO HABITAT 'A' (AREA)
    $RVG     - REVERSION OF LAND FROM HABITAT 'G' (AREA)

$R.K=$RA.JK+$RB.JK+$RC.JK+$RD.JK+$RE.JK+$RF.JK+      19, A
  $RG.JK
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $RA      - AREA OF HABITAT 'A' REMOVED BY HARVEST
                 (AREA)
    $RB      - AREA OF HABITAT 'B' REMOVED BY HARVEST
                 (AREA)
    $RC      - AREA OF HABITAT 'C' REMOVED BY HARVEST
                 (AREA)
    $RD      - AREA OF HABITAT 'D' REMOVED BY HARVEST
                 (AREA)
    $RE      - AREA OF HABITAT 'E' REMOVED BY HARVEST
                 (AREA)
    $RF      - AREA OF HABITAT 'F' REMOVED BY HARVEST
                 (AREA)
    $RG      - AREA OF HABITAT 'G' REMOVED BY HARVEST
                 (AREA)
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```
$TB.KL=ZERO($TOA.JK+CB.K-$RVA.K)                          20, R
    $TB      - TRANSFER LAND TO HABITAT 'B' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOA     - TRANSFER AREA OUT OF HABITAT 'A'
    CB       - CONVERSION OF LAND TO HABITAT 'B' (AREA)
    $RVA     - REVERSION OF LAND FROM HABITAT 'A' (AREA)

$TC.KL=ZERO($TOB.JK+CC.K-$RVB.K)                          21, R
    $TC      - TRANSFER LAND TO HABITAT 'C' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOB     - TRANSFER AREA OUT OF HABITAT 'B'
    CC       - CONVERSION OF LAND TO HABITAT 'C' (AREA)
    $RVB     - REVERSION OF LAND FROM HABITAT 'B' (AREA)

$TD.KL=ZERO($TOC.JK+CD.K-$RVC.K)                          22, R
    $TD      - TRANSFER LAND TO HABITAT 'D' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOC     - TRANSFER AREA OUT OF HABITAT 'C'
    CD       - CONVERSION OF LAND TO HABITAT 'D' (AREA)
    $RVC     - REVERSION OF LAND FROM HABITAT 'C' (AREA)

$TE.KL=ZERO($TOD.JK+CE.K-$RVD.K)                          23, R
    $TE      - TRANSFER LAND TO HABITAT 'E' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOD     - TRANSFER AREA OUT OF HABITAT 'D'
    CE       - CONVERSION OF LAND TO HABITAT 'E' (AREA)
    $RVD     - REVERSION OF LAND FROM HABITAT 'D' (AREA)

$TF.KL=ZERO($TOE.JK+CF.K-$RVE.K)                          24, R
    $TF      - TRANSFER LAND TO HABITAT 'F' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOE     - TRANSFER AREA OUT OF HABITAT 'E'
    CF       - CONVERSION OF LAND TO HABITAT 'F' (AREA)
    $RVE     - REVERSION OF LAND FROM HABITAT 'E' (AREA)

$TG.KL=ZERO($TOF.JK+CG.K-$RVF.K)                          25, R
    $TG      - TRANSFER LAND TO HABITAT 'G' (AREA)
    ZERO     - FUNCTION ENSURES A VALUE EQUAL TO OR
                 GREATER THAN ZERO
    $TOF     - TRANSFER AREA OUT OF HABITAT 'F'
    CG       - CONVERSION OF LAND TO HABITAT 'G' (AREA)
    $RVF     - REVERSION OF LAND FROM HABITAT 'F' (AREA)

$SBO.K=SB.JK+$SCO.K                                       26, A
    $SBO     - SALE OF HABITAT 'B' AND OLDER (AREA
    SB       - AMOUNT OF HABITAT 'B' TO SELL (AREA)
    $SCO     - SALE OF HABITAT 'C' AND OLDER (AREA

$SCO.K=SC.JK+$SDO.K                                       27, A
    $SCO     - SALE OF HABITAT 'C' AND OLDER (AREA
    SC       - AMOUNT OF HABITAT 'C' TO SELL (AREA)
    $SDO     - SALE OF HABITAT 'D' AND OLDER (AREA
$SDO.K=SD.JK+$SEO.K                                          28, A
    $SDO     - SALE OF HABITAT 'D' AND OLDER (AREA
    SD       - AMOUNT OF HABITAT 'D' TO SELL (AREA)
    $SEO     - SALE OF HABITAT 'E' AND OLDER (AREA

$SEO.K=SE.JK+$SFO.K                                          29, A
    $SEO     - SALE OF HABITAT 'F' AND OLDER (AREA
    SE       - AMOUNT OF HABITAT 'E' TO SELL (AREA)
    $SFO     - SALE OF HABITAT 'F' AND OLDER (AREA

$SFO.K=SF.JK+SG.JK                                           30, A
    $SFO     - SALE OF HABITAT 'F' AND OLDER (AREA
    SF       - AMOUNT OF HABITAT 'F' TO SELL (AREA)
    SG       - AMOUNT OF HABITAT 'G' TO SELL (AREA)

$FLA.K=(OBTAH.K*FA)/(MAX($AA,HA))                            31, A
    $FLA     - FLOW OF HABITAT 'A' (AREA/YEAR)
    OBTAH    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 FOREST TYPE(AREA)
    FA       - FRACTION OF TYPE DIVERTED FROM HABITAT 'A'
                 (PERCENT)
    MAX      - FUNCTION SELECTS MAXIMUM VALUE
    $AA      - YOUNGEST AGE OF HABITAT 'A' (YEARS)
    HA       - HARVEST AGE DESIRED FOR HABITAT 'A' (YEARS)

$FLB.K=(OBTAH.K*FB)/(MAX($AB,HB))                            32, A
    $FLB     - FLOW OF HABITAT 'B' (AREA/YEAR)
    OBTAH    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 FOREST TYPE(AREA)
    FB       - FRACTION OF TYPE DIVERTED FROM HABITAT 'B'
                 (PERCENT)
    MAX      - FUNCTION SELECTS MAXIMUM VALUE
    $AB      - YOUNGEST AGE OF HABITAT 'B' (YEARS)
    HB       - HARVEST AGE DESIRED FOR HABITAT 'B' (YEARS)

$FLC.K=(OBTAH.K*FC)/(MAX($AC,HC))                            33, A
    $FLC     - FLOW OF HABITAT 'C' (AREA/YEAR)
    OBTAH    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 FOREST TYPE(AREA)
    FC       - FRACTION OF TYPE DIVERTED FROM HABITAT 'C'
                 (PERCENT)
    MAX      - FUNCTION SELECTS MAXIMUM VALUE
    $AC      - YOUNGEST AGE OF HABITAT 'C' (YEARS)
    HC       - HARVEST AGE DESIRED FOR HABITAT 'C' (YEARS)

$FLD.K=(OBTAH.K*FD)/(MAX($AD,HD))                            34, A
    $FLD     - FLOW OF HABITAT 'D' (AREA/YEAR)
    OBTAH    - MACRO FOR COMPUTING AREA OF A SPECIFIED
                 FOREST TYPE(AREA)
    FD       - FRACTION OF TYPE DIVERTED FROM HABITAT 'D'
                 (PERCENT)
    MAX      - FUNCTION SELECTS MAXIMUM VALUE
    $AD      - YOUNGEST AGE OF HABITAT 'D' (YEARS)
    HD       - HARVEST AGE DESIRED FOR HABITAT 'D' (YEARS)
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  LE.K=(OBTAH.K*FE)/(MAX($AE,HE))                                  35, A
    $FLE    - FLOW OF HABITAT 'E' (AREA/YEAR)
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    FE      - FRACTION OF TYPE DIVERTED FROM HABITAT 'E'
                (PERCENT)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    $AE     - YOUNGEST AGE OF HABITAT 'E' (YEARS)
    HE      - HARVEST AGE DESIRED FOR HABITAT 'E' (YEARS)

$FLG.K=(OPTAH.K*FG)/(MAX($AG,HG))                                  36, A
    $FLG    - FLOW OF HABITAT 'G' (AREA/YEAR)
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    FG      - FRACTION OF TYPE DIVERTED FROM HABITAT 'G'
                (PERCENT)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    $AG     - YOUNGEST AGE OF HABITAT 'G' (YEARS)
    HG      - HARVEST AGE DESIRED FOR HABITAT 'G' (YEARS)

$FLF.K=(OBTAH.K*FF)/(MAX($AF,HF))                                  37, A
    $FLF    - FLOW OF HABITAT 'F' (AREA/YEAR)
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    FF      - FRACTION OF TYPE DIVERTED FROM HABITAT 'F'
                (PERCENT)
    MAX     - FUNCTION SELECTS MAXIMUM VALUE
    $AF     - YOUNGEST AGE OF HABITAT 'F' (YEARS)
    HF      - HARVEST AGE DESIRED FOR HABITAT 'F' (YEARS)

$FAO.K=$FLA.K+$FBO.K                                               38, A
    $FAO    - FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
    $FLA    - FLOW OF HABITAT 'A' (AREA/YEAR)
    $FBO    - FLOW OF HABITAT 'B' AND OLDER (AREA/YEAR)

$FBO.K=$FLB.K+$FCO.K                                               39, A
    $FBO    - FLOW OF HABITAT 'B' AND OLDER (AREA/YEAR)
    $FLB    - FLOW OF HABITAT 'B' (AREA/YEAR)
    $FCO    - FLOW OF HABITAT 'C' AND OLDER (AREA/YEAR)

$FCO.K=$FLC.K+$FDO.K                                               40, A
    $FCO    - FLOW OF HABITAT 'C' AND OLDER (AREA/YEAR)
    $FLC    - FLOW OF HABITAT 'C' (AREA/YEAR)
    $FDO    - FLOW OF HABITAT 'D' AND OLDER (AREA/YEAR)

$FDO.K=$FLD.K+$FEO.K                                               41, A
    $FDO    - FLOW OF HABITAT 'D' AND OLDER (AREA/YEAR)
    $FLD    - FLOW OF HABITAT 'D' (AREA/YEAR)
    $FEO    - FLOW OF HABITAT 'E' AND OLDER (AREA/YEAR)

$FEO.K=$FLE.K+$FFO.K                                               42, A
    $FEO    - FLOW OF HABITAT 'E' AND OLDER (AREA/YEAR)
    $FLE    - FLOW OF HABITAT 'F' (AREA/YEAR)
    $FFO    - FLOW OF HABITAT 'F' AND OLDER (AREA/YEAR)
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$FFO.K=$FLF.K+$FLG.K                                   43, A
$AA=1                                                  43.1, N
$AB=DA+1                                               43.2, N
$AC=DA+DB+1                                            43.3, N
$AD=DA+DB+DC+1                                         43.4, N
$AE=DA+DB+DC+DD+1                                      43.5, N
$AF=DA+DB+DC+DD+DE+1                                   43.6, N
$AG=DA+DB+DC+DD+DE+DF+1                                43.7, N
    $FFO    - FLOW OF HABITAT 'F' AND OLDER (AREA/YEAR)
    $FLF    - FLOW OF HABITAT 'F' (AREA/YEAR)
    $FLG    - FLOW OF HABITAT 'G' (AREA/YEAR)
    $AA     - YOUNGEST AGE OF HABITAT 'A' (YEARS)
    $AB     - YOUNGEST AGE OF HABITAT 'B' (YEARS)
    DA      - DELAY FOR HABITAT 'A' (YEARS)
    $AC     - YOUNGEST AGE OF HABITAT 'C' (YEARS)
    DB      - DELAY FOR HABITAT 'B' (YEARS)
    $AD     - YOUNGEST AGE OF HABITAT 'D' (YEARS)
    DC      - DELAY FOR HABITAT 'C' (YEARS)
    $AE     - YOUNGEST AGE OF HABITAT 'E' (YEARS)
    DD      - DELAY FOR HABITAT 'D' (YEARS)
    $AF     - YOUNGEST AGE OF HABITAT 'F' (YEARS)
    DE      - DELAY FOR HABITAT 'E' (YEARS)
    $AG     - YOUNGEST AGE OF HABITAT 'G' (YEARS)
    DF      - DELAY FOR HABITAT 'F' (YEARS)

$SO.K=NORMRN(ISO,ISD)                                  44, A
    $SC     - SIZE OF OPENING (AREA)
    NORMRN  - FUNCTION FOR RANDOM NUMBERS NORMALLY
                DISTRIBUTED
    ISO     - INITIAL SIZE OF OPENINGS (AREA)
    ISD     - INITIAL STANDARD DEVIATION OF SIZE OF
                OPENINGS (AREA)

PTI.K=VT.K/$TIM.K                                      45, A
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    VT      - TOTAL VOLUME OF TIMBER REMOVED FROM A
                FOREST TYPE (VOLUME)
    $TIM    - TIMBER MAXIMUM YIELD FOR OPTIMUM ROTATION
                (VOLUME)

VT.K=$VA.K+$VB.K+$VC.K+$VD.K+$VE.K+$VF.K+$VG.K         46, A
    VT      - TOTAL VOLUME OF TIMBER REMOVED FROM A
                FOREST TYPE (VOLUME)
    $VA     - VOLUME OF TIMBER REMOVED FROM HABITAT 'A'
    $VB     - VOLUME OF TIMBER REMOVED FROM HABITAT 'B'
    $VC     - VOLUME OF TIMBER REMOVED FROM HABITAT 'C'
    $VD     - VOLUME OF TIMBER REMOVED FROM HABITAT 'D'
    $VE     - VOLUME OF TIMBER REMOVED FROM HABITAT 'E'
    $VF     - VOLUME OF TIMBER REMOVED FROM HABITAT 'F'
    $VG     - VOLUME OF TIMBER REMOVED FROM HABITAT 'G'
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$TIM.K=(OBTAH.K/TMR)*$TYI*YST                               47, A
$TYI=TABHL(TTYI.TMR,0.320,10)                               47.1, N
    $TIM    - TIMBER MAXIMUM YIELD FOR OPTIMUM ROTATION
                (VOLUME)
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    TMR     - TIMBER ROTATION FOR MAXIMUM YIELD (YEARS)
    $TYI    - TIMBER YIELD INDEX FOR OPTIMUM ROTATION
                (DIMENSIONLESS)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)

TNH.K=$NOA.K+$NOB.K+$NOC.K+$NOD.K+$NOE.K+$NOF.K+            48, A
  $NOG.K
    TNH     - TOTAL NUMBER OF OPENINGS FOR A TYPE
    $NOA    - NUMBER OF OPENINGS FOR HABITAT 'A'
    $NOB    - NUMBER OF OPENINGS FOR HABITAT 'B'
    $NOC    - NUMBER OF OPENINGS FOR HABITAT 'C'
    $NOD    - NUMBER OF OPENINGS FOR HABITAT 'D'
    $NOE    - NUMBER OF OPENINGS FOR HABITAT 'E'
    $NOF    - NUMBER OF OPENINGS FOR HABITAT 'F'
    $NOG    - NUMBER OF OPENINGS FOR HABITAT 'G'

WOH.K=$OA.K+$OB.K+$OC.K+$OD.K+$OE.K+$OF.K+$OG.K             49, A
    WOH     - WEIGHTED OPENING SIZE FOR A TYPE
    $OA     - OPENING SIZE DISTRIBUTION FOR HABITAT 'A'
                (AREA)
    $OB     - OPENING SIZE DISTRIBUTION FOR HABITAT 'B'
                (AREA)
    $OC     - OPENING SIZE DISTRIBUTION FOR HABITAT 'C'
                (AREA)
    $OD     - OPENING SIZE DISTRIBUTION FOR HABITAT 'D'
                (AREA)
    $OE     - OPENING SIZE DISTRIBUTION FOR HABITAT 'E'
                (AREA)
    $OF     - OPENING SIZE DISTRIBUTION FOR HABITAT 'F'
                (AREA)
    $OG     - OPENING SIZE DISTRIBUTION FOR HABITAT 'G'
                (AREA)

$OA.K=($RA.K/($R.K+1E-6))*$SOA.K                            50, A
    $OA     - OPENING SIZE DISTRIBUTION FOR HABITAT 'A'
                (AREA)
    $RA     - AREA OF HABITAT 'A' REMOVED BY HARVEST
                (AREA)
    $R      - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                (AREA)
    $SOA    - SIZE OF OPENINGS FOR HABITAT 'A'
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$OB.K=($RB.K/($R.K+1E-6))*$SOB.K                              51, A
    $OB      - OPENING SIZE DISTRIBUTION FOR HABITAT 'B'
                 (AREA)
    $RB      - AREA OF HABITAT 'B' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOB     - SIZE OF OPENINGS FOR HABITAT 'B'

$OC.K=($RC.K/($R.K+1E-6))*$SOC.K                              52, A
    $OC      - OPENING SIZE DISTRIBUTION FOR HABITAT 'C'
                 (AREA)
    $RC      - AREA OF HABITAT 'C' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOC     - SIZE OF OPENINGS FOR HABITAT 'C'

$OD.K=($RD.K/($R.K+1E-6))*$SOD.K                              53, A
    $OD      - OPENING SIZE DISTRIBUTION FOR HABITAT 'D'
                 (AREA)
    $RD      - AREA OF HABITAT 'D' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOD     - SIZE OF OPENINGS FOR HABITAT 'D'

$OE.K=($RE.K/($R.K+1E-6))*$SOE.K                              54, A
    $OE      - OPENING SIZE DISTRIBUTION FOR HABITAT 'E'
                 (AREA)
    $RE      - AREA OF HABITAT 'E' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOE     - SIZE OF OPENINGS FOR HABITAT 'E'

$OF.K=($RF.K/($R.K+1E-6))*$SOF.K                              55, A
    $OF      - OPENING SIZE DISTRIBUTION FOR HABITAT 'F'
                 (AREA)
    $RF      - AREA OF HABITAT 'F' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOF     - SIZE OF OPENING FACTOR (DIMENSIONLESS)

$OG.K=($RG.K/($R.K+1E-6))*$SOG.K                              56, A
    $OG      - OPENING SIZE DISTRIBUTION FOR HABITAT 'G'
                 (AREA)
    $RG      - AREA OF HABITAT 'G' REMOVED BY HARVEST
                 (AREA)
    $R       - TOTAL AREA OF A TYPE REMOVED BY HARVEST
                 (AREA)
    $SOG     - SIZE OF OPENINGS FOR HABITAT 'G'

MEND
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FOREST TYPE SECTOR

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BIVY.K=OBTAH(ISE,ISA,IP6,IP8,IP1,IMT,IOG,CSE,CSA,     2, A
  CP6,CP8,CP1,CMT,COG,DSE,DSA,DP6,DP8,DP1,DMT,DOG,
  HSE,HSA,HP6,HP8,HP1,HMT,HOG,SEF,SAF,P6F,P8F,P1F,
  MTF,OGF,TTYI,YST,TMR,ISO,ISD,SES.K,SAS.K,P6S.K,
  P8S.K,P1S.K,MTS.K,OGS.K,PTI.K,VT.K,NOP.K,OPS.K,
  SED.K,SAP.K,P6.K,P8.K,P1.K,MT.K,OG.K)
    BIVY    - SPECIFIC NAME OF A FOREST TYPE
    OBTAH   - MACRO FOR COMPUTING AREA OF A SPECIFIED
                FOREST TYPE(AREA)
    ISE     - INVENTORY FOR BIVY TYPE SEEDLINGS (AREA)
    ISA     - INVENTORY FOR BIVY TYPE SAPLINGS (AREA)
    IP6     - INVENTORY FOR BIVY TYPE POLE 6 (AREA)
    IP8     - INVENTORY FOR BIVY TYPE POLE 8 (AREA)
    IP1     - INVENTORY FOR BIVY TYPE POLE 10 (AREA)
    IMT     - INVENTORY FOR BIVY TYPE MATURE TIMBER
                (AREA)
    IOG     - INVENTORY FOR BIVY TYPE OLD GROWTH (AREA)
    CSE     - CONVERSION OF LAND TO BIVY TYPE AS
                SEEDLINGS (AREA)
    CSA     - CONVERSION OF LAND TO BIVY TYPE AS SAPLINGS
                (AREA)
    CP6     - CONVERSION OF LAND TO BIVY TYPE AS POLE 6
                (AREA)
    CP8     - CONVERSION OF LAND TO BIVY TYPE AS POLE 8
                (AREA)
    CP1     - CONVERSION OF LAND TO BIVY TYPE AS POLE 10
                (AREA)
    CMT     - CONVERSION OF LAND TO BIVY TYPE AS MATURE
                TIMBER (AREA)
    COG     - CONVERSION OF LAND TO BIVY TYPE AS OLD
                GROWTH (AREA)
    DSE     - DELAY FOR BIVY TYPE SEEDLINGS (YEARS)
    DSA     - DELAY FOR BIVY TYPE SAPLINGS (YEARS)
    DP6     - DELAY FOR BIVY TYPE POLE 6 (YEARS)
    DP8     - DELAY FOR BIVY TYPE POLE 8 (YEARS)
    DP1     - DELAY FOR BIVY TYPE POLE 10 (YEARS)
    DMT     - DELAY FOR BIVY TYPE MATURE TIMBER (YEARS)
    DOG     - DELAY FOR BIVY TYPE OLD GROWTH (YEARS)
    HSE     - AGE SPECIFIED FOR HARVESTING BIVY SEEDLINGS
                (YEARS)
    HSA     - AGE SPECIFIED FOR HARVESTING BIVY SAPLINGS
                (YEARS)
    HP6     - AGE SPECIFIED FOR HARVESTING BIVY POLE 6
                (YEARS)
    HP8     - AGE SPECIFIED FOR HARVESTING BIVY POLE 8
                (YEARS)
    HP1     - AGE SPECIFIED FOR HARVESTING BIVY POLE 10
                (YEARS)
    HMT     - AGE SPECIFIED FOR HARVESTING BIVY MATURE
                TIMBER (YEARS)
    HOG     - AGE SPECIFIED FOR HARVESTING BIVY OLD
                GROWTH (YEARS)
    SEF     - FRACTION OF BIVY TYPE HARVESTED AS SEEDLING
                HABITAT
    SAF     - FRACTION OF BIVY TYPE HARVESTED AS SAPLING
                HABITAT
    P6F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-6
                HABITAT
    P8F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-8
                HABITAT
    P1F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-10
                HABITAT
    MTF     - FRACTION OF BIVY TYPE HARVESTED AS MATURE
                TIMBER HABITAT
    OGF     - FRACTION OF BIVY TYPE HARVESTED AS OLD
                GROWTH HABITAT
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    TMR     - TIMBER ROTATION FOR MAXIMUM YIELD (YEARS)
    ISO     - INITIAL SIZE OF OPENINGS (AREA)
    ISD     - INITIAL STANDARD DEVIATION OF SIZE OF
                OPENINGS (AREA)
    SES     - BIVY TYPE SELL SEEDLINGS (AREA)
    SAS     - BIVY TYPE SELL SAPLINGS (AREA)
    P6S     - BIVY TYPE SELL POLE 6 (AREA)
    P8S     - BIVY TYPE SELL POLE 8 (AREA)
    P1S     - BIVY TYPE SELL POLE 10 (AREA)
    MTS     - BIVY TYPE SELL MATURE TIMBER (AREA)
    OGS     - BIVY TYPE SELL OLD GROWTH (AREA)
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    VT      - TOTAL VOLUME OF TIMBER REMOVED FROM A
                FOREST TYPE (VOLUME)
    NOP     - NUMBER OF OPENINGS
    OPS     - OPENING SIZE DISTRIBUTION (AREA)
    SED     - SEEDLING HABITAT (AREA)
    SAP     - SAPLING HABITAT (AREA)
    P6      - POLE SIX HABITAT (AREA)
    P8      - POLE EIGHT HABITAT (AREA)
    P1      - POLE TEN HABITAT (AREA)
    MT      - MATURE TIMBER HABITAT (AREA)
    OG      - OLD GROWTH HABITAT (AREA)

CSE.K=ZERO(NS)                                                3, A
    CSE     - CONVERSION OF LAND TO BIVY TYPE AS
                SEEDLINGS (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

CSA.K=ZERO(NS)                                                4, A
    CSA     - CONVERSION OF LAND TO BIVY TYPE AS SAPLINGS
                (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

CP6.K=ZERO(NS)                                                5, A
    CP6     - CONVERSION OF LAND TO BIVY TYPE AS POLE 6
                (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO
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CP8.K=ZERO(NS)                                           6, A
    CP8     - CONVERSION OF LAND TO BIVY TYPE AS POLE 8
                (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

CP1.K=ZERO(NS)                                           7, A
    CP1     - CONVERSION OF LAND TO BIVY TYPE AS POLE 10
                (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

CMT.K=ZERO(NS)                                           8, A
    CMT     - CONVERSION OF LAND TO BIVY TYPE AS MATURE
                TIMBER (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO

COG.K=ZERO(NS)                                           9, A
ISE=200/ISA=1254/IP6=1843/IP8=740/IP1=1808/IMT=366/ 9.1, C
  IOG=185
DSE=5/DSA=30/DP6=15/DP8=15/DP1=20/DMT=35/DOG=180    9.2, C
TTYI=0/.23/.41/.6/.81/1/1.18/1.33/1.47/1.61/1.75/   9.3, T
  1.85/1.89/1.92/1.94/1.96/1.97/1.98/1.99/2/2.01/
  2.02/2.02/2.03/2.04/2.04/2.05/2.06/2.06/2.07/
  2.08/2.08/2.09
YST=2520                                            9.6, C
TMR=50                                              9.7, C
    COG     - CONVERSION OF LAND TO BIVY TYPE AS OLD
                GROWTH (AREA)
    ZERO    - FUNCTION ENSURES A VALUE EQUAL TO OR
                GREATER THAN ZERO
    NS      - NULL STANDARD,EQUALS ZERO
    ISE     - INVENTORY FOR BIVY TYPE SEEDLINGS (AREA)
    ISA     - INVENTORY FOR BIVY TYPE SAPLINGS (AREA)
    IP6     - INVENTORY FOR BIVY TYPE POLE 6 (AREA)
    IP8     - INVENTORY FOR BIVY TYPE POLE 8 (AREA)
    IP1     - INVENTORY FOR BIVY TYPE POLE 10 (AREA)
    IMT     - INVENTORY FOR BIVY TYPE MATURE TIMBER
                (AREA)
    IOG     - INVENTORY FOR BIVY TYPE OLD GROWTH (AREA)
    DSE     - DELAY FOR BIVY TYPE SEEDLINGS (YEARS)
    DSA     - DELAY FOR BIVY TYPE SAPLINGS (YEARS)
    DP6     - DELAY FOR BIVY TYPE POLE 6 (YEARS)
    DP8     - DELAY FOR BIVY TYPE POLE 8 (YEARS)
    DP1     - DELAY FOR BIVY TYPE POLE 10 (YEARS)
    DMT     - DELAY FOR BIVY TYPE MATURE TIMBER (YEARS)
    DOG     - DELAY FOR BIVY TYPE OLD GROWTH (YEARS)
    TTYI    - TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                UNITS/UNIT AREA)
    YST     - YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                VOLUME/ACRE)
    TMR     - TIMBER ROTATION FOR MAXIMUM YIELD (YEARS)
  SUPPLEMENTARY INFORMATION

PSE.K=SED.K/BIVY.K                                               10, A
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                 HABITAT (PERCENT)
    SED      - SEEDLING HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PSA.K=SAP.K/BIVY.K                                               11, A
    PSA      - PROPORTION OF TOTAL AREA IN SAPLING HABITAT
                 (PERCENT)
    SAP      - SAPLING HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PP6.K=P6.K/BIVY.K                                                12, A
    PP6      - PROPORTION OF TOTAL AREA IN POLE SIX
                 HABITAT (PERCENT)
    P6       - POLE SIX HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PP8.K=P8.K/BIVY.K                                                13, A
    PP8      - PROPORTION OF TOTAL AREA IN POLE EIGHT
                 HABITAT (PERCENT)
    P8       - POLE EIGHT HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PP1.K=P1.K/BIVY.K                                                14, A
    PP1      - PROPORTION OF TOTAL AREA IN POLE TEN
                 HABITAT (PERCENT)
    P1       - POLE TEN HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PMT.K=MT.K/BIVY.K                                                15, A
    PMT      - PROPORTION OF TOTAL AREA IN MATURE TIMBER
                 HABITAT (PERCENT)
    MT       - MATURE TIMBER HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

POG.K=OG.K/BIVY.K                                                16, A
    POG      - PROPORTION OF TOTAL AREA IN OLD GROWTH
                 HABITAT (PERCENT)
    OG       - OLD GROWTH HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PSEA.K=(SED.K+SAP.K)/BIVY.K                                      17, A
    PSEA     - PROPORTION OF TOTAL AREA IN SEEDLINGS AND
                 SAPLINGS (PERCENT)
    SED      - SEEDLING HABITAT (AREA)
    SAP      - SAPLING HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE
  O8M.K=(P8.K+P1.K+MT.K)/BIVY.K                                    18, A
    PO8M     - PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN
                 AND MATURE (PERCENT)
    P8       - POLE EIGHT HABITAT (AREA)
    P1       - POLE TEN HABITAT (AREA)
    MT       - MATURE TIMBER HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

P1M.K=(P1.K+MT.K)/BIVY.K                                           19, A
    P1M      - PROPORTION OF TOTAL AREA IN POLE TEN AND
                 MATURE (PERCENT)
    P1       - POLE TEN HABITAT (AREA)
    MT       - MATURE TIMBER HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

PMO.K=(MT.K+OG.K)/BIVY.K                                           20, A
    PMO      - PROPORTION OF TOTAL AREA IN MATURE AND OLD
                 GROWTH (PERCENT)
    MT       - MATURE TIMBER HABITAT (AREA)
    OG       - OLD GROWTH HABITAT (AREA)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

OPM.K=NOP.K/(BIVY.K/640)                                           21, A
    OPM      - OPENINGS PER SQUARE MILE (NUMBER)
    NOP      - NUMBER OF OPENINGS
    BIVY     - SPECIFIC NAME OF A FOREST TYPE

  BENEFIT INFORMATION

SEMT.K=TABHL(TSEMT,OPM.K,0,1,.2)                                   22, A
TSEMT=0/.3/.6/.8/.9/1                                              22.1,
    SEMT     - SEDIMENT INDEX
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TSEMT    - SEDIMENT TABLE
    OPM      - OPENINGS PER SQUARE MILE (NUMBER)

UGL.K=UGS.K*UGN.K*UGO.K                                            23, A
    UGL      - UGLINESS INDEX
    UGS      - UGLY DUE TO SEEDLING HABITAT
    UGN      - UGLINESS DUE TO FREQUENCY OF OPENINGS
    UGO      - UGLY DUE TO OPENING SIZE

UGS.K=TABHL(TUGS,PSE.K,0,.06,.01)                                  24, A
TUGS=0/.1/.2/.3/.5/.7/1                                            24.1,
    UGS      - UGLY DUE TO SEEDLING HABITAT
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TUGS     - TABLE, UGLINESS DUE TO SEEDLINGS
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                 HABITAT (PERCENT)

UGN.K=TABHL(TUGN,OPM.K,0,.8,.2)                                    25, A
TUGN=1/.9/.7/.4/.01                                                25.1,
    UGN      - UGLINESS DUE TO FREQUENCY OF OPENINGS
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TUGN     - TABLE UGLY DUE TO OPENING FREQUENCY
    OPM      - OPENINGS PER SQUARE MILE (NUMBER)
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UGO.K=TABHL(TUGO,OPS.K,0,30,3)                                26, A
TUGO=0/.50/.65/.70/.75/.80/.85/.90/.95/.97/1                  26.1, T
    UGO      - UGLY DUE TO OPENING SIZE
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TUGO     - TABLE UGLY DUE TO OPENING SIZE
    OPS      - OPENING SIZE DISTRIBUTION (AREA)

VIS.K=VSE.K*VBAL.K*VPOG.K                                     27, A
    VIS      - VISUAL INDEX
    VSE      - CONTRIBUTION OF SEEDLINGS TO VISUAL APPEAL
    VBAL     - VISUAL DUE TO BALANCE
    VPOG     - VISUAL DUE TO OLD GROWTH

VSE.K=TABHL(TVSE,PSE.K,.01,.07,.01)                           28, A
TVSE=.2/.6/.9/1/.9/.6/.2                                      28.1, T
    VSE      - CONTRIBUTION OF SEEDLINGS TO VISUAL APPEAL
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TVSE     - TABLE VISUAL DUE TO SEEDLINGS
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                 HABITAT (PERCENT)

VBAL.K=TABHL(TVBA,BAL.K,0,2,.5)                               29, A
TVBA=.4/.7/1/.7/.4                                            29.1, T
    VBAL     - VISUAL DUE TO BALANCE
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TVBA     - TABLE VISUAL DUE TO BALANCE
    BAL      - BALANCE IN CONTRASTING HEIGHTS OF TREES

BAL.K=(P8.K+P1.K+MT.K)/(SED.K+SAP.K+P6.K)                     30, A
    BAL      - BALANCE IN CONTRASTING HEIGHTS OF TREES
    P8       - POLE EIGHT HABITAT (AREA)
    P1       - POLE TEN HABITAT (AREA)
    MT       - MATURE TIMBER HABITAT (AREA)
    SED      - SEEDLING HABITAT (AREA)
    SAP      - SAPLING HABITAT (AREA)
    P6       - POLE SIX HABITAT (AREA)

VPOG.K=TABHL(TVPO,POG.K,0,.7,.1)                              31, A
TVPO=.4/.7/.9/1/.9/.8/.6/.4                                   31.1, T
    VPOG     - VISUAL DUE TO OLD GROWTH
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TVPO     - TABLE VISUAL DUE TO OLD GROWTH
    POG      - PROPORTION OF TOTAL AREA IN OLD GROWTH
                 HABITAT (PERCENT)

DEER.K=HTD.K*OTD.K*DMA.K                                      32, A
    DEER     - DEER HABITAT INDEX
    HTD      - DEER HABITAT DUE TO SEEDLINGS
    OTD      - DEER HABITAT DUE TO OPENING SIZE
    DMA      - DEER HABITAT DUE TO HARD MAST
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```
HTD.K=TABHL(THTD,PSE.K,0,.07,.01)                              33, A
THTD=0/.1/.2/.5/.7/.8/.9/1                                     33.1, T
    HTD     - DEER HABITAT DUE TO SEEDLINGS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    THTD    - TABLE DEER HABITAT DUE TO SEEDLINGS
    PSE     - PROPORTION OF TOTAL AREA IN SEEDLING
                HABITAT (PERCENT)

OTD.K=TABHL(TOTD,OPS.K,0,60,6)                                 34, A
TOTD=1/1/.97/.93/.9/.85/.8/.7/.6/.5/.45                        34.1, T
    OTD     - DEER HABITAT DUE TO OPENING SIZE
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TOTD    - TABLE DEER HABITAT DUE TO OPENING SIZE
    OPS     - OPENING SIZE DISTRIBUTION (AREA)

DMA.K=TABHL(TDMA,PIM.K,0,.2,.05)                               35, A
TDMA=.1/.2/.5/.8/1                                             35.1, T
    DMA     - DEER HABITAT DUE TO HARD MAST
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TDMA    - TABLE DEER HABITAT DUE TO HARD MAST
    PIM     - PROPORTION OF TOTAL AREA IN POLE TEN AND
                MATURE (PERCENT)

SQU.K=THS.K*SDT.K                                              36, A
    SQU     - SQUIRREL HABITAT INDEX
    THS     - SQUIRREL HABITAT DUE TO HARD MAST
    SDT     - SQUIRREL HABITAT DUE TO DEN TREES IN OLD
                GROWTH

THS.K=TABHL(TTHS,POBM.K,0,.4,.1)                               37, A
TTHS=0/.2/.4/.8/1                                              37.1, T
    THS     - SQUIRREL HABITAT DUE TO HARD MAST
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTHS    - TABLE SQUIRREL HABITAT DUE TO HARD MAST
    POBM    - PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN
                AND MATURE (PERCENT)

SDT.K=TABHL(TSDT,POG.K,0,.3,.1)                                38, A
TSDT=.1/.7/.8/1                                                38.1, T
    SDT     - SQUIRREL HABITAT DUE TO DEN TREES IN OLD
                GROWTH
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TSDT    - TABLE SQUIRREL HABITAT DUE TO OLD GROWTH
    POG     - PROPORTION OF TOTAL AREA IN OLD GROWTH
                HABITAT (PERCENT)

TUR.K=TURT.K*TURO.K                                            39, A
    TUR     - TURKEY HABITAT INDEX
    TURT    - TURKEY HABITAT DUE TO HARD MAST
    TURO    - TURKEY HABITAT DUE TO SIZE OF OPENINGS
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TURT.K=TABHL(TTRT,PO8M.K,0,.5,.1)                    40, A
TTRT=0/.1/.2/.5/.8/1                                 40.1, T
    TURT    - TURKEY HABITAT DUE TO HARD MAST
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTRT    - TABLE TURKEY HABITAT DUE TO HARD MAST
    PO8M    - PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN
                AND MATURE (PERCENT)

TURO.K=TABHL(TTRO,OPS.K,0,28,2)                      41, A
TTRO=0/.2/.5/.7/.9/1/1/1/1/.9/.8/.7/.6/.5/.4         41.1, T
    TURO    - TURKEY HABITAT DUE TO SIZE OF OPENINGS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTRO    - TABLE TURKEY HABITAT DUE TO OPENING SIZE
    OPS     - OPENING SIZE DISTRIBUTION (AREA)

GRS.K=GRH.K*GRO.K                                    42, A
    GRS     - GROUSE HABITAT INDEX
    GRH     - GROUSE HABITAT DUE TO POLE SIZED STANDS
    GRO     - GROUSE HABITAT DUE TO SIZE OF OPENINGS

GRH.K=TABHL(TGRH,PP6.K,0,.2,.05)                     43, A
TGRH=0/.2/.7/.9/1                                    43.1, T
    GRH     - GROUSE HABITAT DUE TO POLE SIZED STANDS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TGRH    - TABLE GROUSE HABITAT DUE TO POLE STANDS
    PP6     - PROPORTION OF TOTAL AREA IN POLE SIX
                HABITAT (PERCENT)

GRO.K=TABHL(TGRO,OPS.K,0,60,6)                       44, A
TGRO=.8/.9/.95/1/.95/.9/.85/.8/.7/.6/.5              44.1, T
    GRO     - GROUSE HABITAT DUE TO SIZE OF OPENINGS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TGRO    - TABLE GROUSE HABITAT DUE TO SIZE OF
                OPENINGS
    OPS     - OPENING SIZE DISTRIBUTION (AREA)

BEAR.K=BDT.K*BSMT.K*BHMT.K                           45, A
    BEAR    - BEAR HABITAT INDEX
    BDT     - BEAR HABITAT DUE TO DENS IN OLD GROWTH
    BSMT    - BEAR HABITAT DUE TO SOFT MAST
    BHMT    - BEAR HABITAT DUE TO HARD MAST

BDT.K=TABHL(TBDT,POG.K,0,.3,.1)                      46, A
TBDT=.2/.8/.9/1                                      46.1, T
    BDT     - BEAR HABITAT DUE TO DENS IN OLD GROWTH
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TBDT    - TABLE BEAR DENS IN OLD GROWTH
    POG     - PROPORTION OF TOTAL AREA IN OLD GROWTH
                HABITAT (PERCENT)

BSMT.K=TABHL(TBSM,PSEA.K,0,.2,.1)                    47, A
TBSM=0/.5/1                                          47.1, T
    BSMT    - BEAR HABITAT DUE TO SOFT MAST
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TBSM    - TABLE BEAR HABITAT DUE TO SOFT MAST
    PSEA    - PROPORTION OF TOTAL AREA IN SEEDLINGS AND
                SAPLINGS (PERCENT)
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BHMT.K=TABHL(TBHM,PO8M.K,0,.4,.1)                                   48, A
TBHM=0/.2/.4/.8/1                                                   48.1,
    BHMT    - BEAR HABITAT DUE TO HARD MAST
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TBHM    - TABLE BEAR HABITAT DUE TO HARD MAST
    PO8M    - PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN
                AND MATURE (PERCENT)

PIL.K=TABHL(TPIL,POG.K,0,.6,.1)                                     49, A
TPIL=.1/.4/.6/.8/.9/.95/1                                           49.1,
    PIL     - PILEATED WOODPECKER HABITAT INDEX
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TPIL    - TABLE PILEATED HABITAT DUE TO OLD GROWTH
    POG     - PROPORTION OF TOTAL AREA IN OLD GROWTH
                HABITAT (PERCENT)

HAR.K=TABHL(THAR,PMO.K,0,.5,.05)                                    50, A
THAR=.05/.1/.15/.2/.35/.5/.65/.8/.9/.95/1                           50.1,
    HAR     - HAIRY WOODPECKER HABITAT INDEX
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    THAR    - TABLE HAIRY WOODPECKER HABITAT
    PMO     - PROPORTION OF TOTAL AREA IN MATURE AND OLD
                GROWTH (PERCENT)

DON.K=TABHL(TDON,P1M.K,0,.4,.05)                                    51, A
TDON=.1/.15/.3/.4/.6/.8/.9/.95/1                                    51.1,
    DON     - DOWNEY WOODPECKER HABITAT INDEX
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TDON    - TABLE DOWNEY WOODPECKER HABITAT
    P1M     - PROPORTION OF TOTAL AREA IN POLE TEN AND
                MATURE (PERCENT)

FLIC.K=FLF.K*FLN.K*FLO.K                                            52, A
    FLIC    - FLICKER WOODPECKER HABITAT INDEX
    FLF     - FLICKER HABITAT DUE TO OPEN FEEDING AREAS
    FLN     - FLICKER NESTING AREAS
    FLO     - SIZE OF OPENING FOR FLICKER FEEDING

FLF.K=TABHL(TFLF,PSE.K,0,.06,.01)                                   53, A
TFLF=.05/.15/.3/.5/.7/.9/1                                          53.1,
    FLF     - FLICKER HABITAT DUE TO OPEN FEEDING AREAS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TFLF    - TABLE FLICKER OPEN FEEDING AREAS
    PSE     - PROPORTION OF TOTAL AREA IN SEEDLING
                HABITAT (PERCENT)

FLN.K=TABHL(TFLN,PMO.K,0,.2,.05)                                    54, A
TFLN=.5/.8/.9/.95/1                                                 54.1,
    FLN     - FLICKER NESTING AREAS
    TABHL   - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TFLN    - TABLE FLICKER NESTING AREAS
    PMO     - PROPORTION OF TOTAL AREA IN MATURE AND OLD
                GROWTH (PERCENT)
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FLO.K=TABHL(TFLO,OPS.K,0,10,2)                          55, A
TFLO=.05/.1/.5/.9/.95/1                                 55.1, T
    FLO      - SIZE OF OPENING FOR FLICKER FEEDING
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TFLO     - TABLE OPENING SIZE FOR FLICKER FEEDING
    OPS      - OPENING SIZE DISTRIBUTION (AREA)

BLU.K=BBH.K*BBO.K                                       56, A
    BLU      - BLUEBIRD HABITAT INDEX
    BBH      - BLUEBIRD FEEDING AND NESTING HABITAT
    BBO      - SIZE OF OPENINGS FOR BLUEBIRDS

BBH.K=TABHL(TBBH,PSE.K,0,.06,.01)                       57, A
TBBH=0/.1/.2/.4/.7/.9/1                                 57.1, T
    BBH      - BLUEBIRD FEEDING AND NESTING HABITAT
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TBBH     - TABLE BLUEBIRD HABITAT DUE TO SEEDINGS
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                  HABITAT (PERCENT)

BBO.K=TABHL(TBBO,OPS.K,0,60,6)                          58, A
TBBO=0/.6/1/1/1/1/.95/.9/.85/.8/.7                      58.1, T
    BBO      - SIZE OF OPENINGS FOR BLUEBIRDS
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TBBO     - TABLE SIZE OF OPENINGS FOR BLUEBIRDS
    OPS      - OPENING SIZE DISTRIBUTION (AREA)

OVN.K=TABHL(TOVN,PP6.K,0,.3,.05)                        59, A
TOVN=.1/.2/.4/.7/.8/.9/1                                59.1, T
    OVN      - OVEN BIRD HABITAT INDEX
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TOVN     - OVEN BIRD TYPE HABITAT
    PP6      - PROPORTION OF TOTAL AREA IN POLE SIX
                  HABITAT (PERCENT)

TWE.K=TWH.K*TWO.K                                       60, A
    TWE      - TOWHEE TYPE BIRD HABITAT
    TWH      - TOWHEE TYPE HABITAT DUE TO SAPLINGS
    TWO      - OPENING SIZE FOR TOWHEE TYPE HABITAT

TWH.K=TABHL(TTWE,PSA.K,0,.45,.05)                       61, A
TTWE=0/.1/.2/.4/.6/.8/.85/.9/.95/1                      61.1, T
    TWH      - TOWHEE TYPE HABITAT DUE TO SAPLINGS
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTWE     - TABLE TOWHEE TYPE HABITAT
    PSA      - PROPORTION OF TOTAL AREA IN SAPLING HABITAT
                  (PERCENT)

TWO.K=TABHL(TTWO,OPS.K,0,5,1)                           62, A
TTWO=.1/.5/.7/.8/.9/1                                   62.1, T
    TWO      - OPENING SIZE FOR TOWHEE TYPE HABITAT
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TTWO     - TABLE FOR OPENING SIZE FOR TOWHEE TYPE
                  BIRDS
    OPS      - OPENING SIZE DISTRIBUTION (AREA)
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PWE.K=TABHL(TPWE,PMC.K,0,.7,.1)                               63, A
TPWE=.1/.2/.4/.7/.8/.9/.95/1                                  63.1, T
    PWE      - PEWEE HABITAT INDEX (DIMENSIONLESS)
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TPWE     - TABLE PEWEE HABITAT
    PMC      - PROPORTION OF TOTAL AREA IN MATURE AND OLD
                  GROWTH (PERCENT)

CQ.K=(TQ.K+NHQ)/NHQ                                           64, A
NHQ=LOGN(NH)                                                  64.1, N
NH=7                                                          64.2, C
    CQ       - CONSTRAINT QUANTUM (DIMENSIONLESS)
    TQ       - TOTAL QUANTUM FOR HABITATS (DIMENSIONLESS)
    NHQ      - MAXIMUM CONSTRAINT FOR NUMBER OF HABITATS
                  (DIMENSIONLESS)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM
    NH       - NUMBER OF HABITAT CLASSES

TQ.K=(SEQ.K+SAQ.K+P6Q.K+P8Q.K+P1Q.K+MTQ.K+OGQ.K)             65, A
    TQ       - TOTAL QUANTUM FOR HABITATS (DIMENSIONLESS)
    SEQ      - QUANTUM FOR SEEDLINGS (DIMENSIONLESS)
    SAQ      - QUANTUM FOR SAPLINGS (DIMENSIONLESS)
    P6Q      - QUANTUM FOR POLE-6 HABITAT (DIMENSIONLESS)
    P8Q      - QUANTUM FOR POLE-8 HABITAT (DIMENSIONLESS)
    P1Q      - QUANTUM FOR POLE-1 HABITAT (DIMENSIONLESS)
    MTQ      - QUANTUM FOR MATURE TIMBER HABITAT
                  (DIMENSIONLESS)
    OGQ      - QUANTUM FOR OLD GROWTH HABITAT
                  (DIMENSIONLESS)

SEQ.K=PSE.K*LOGN(PSE.K)                                       66, A
    SEQ      - QUANTUM FOR SEEDLINGS (DIMENSIONLESS)
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                  HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

SAQ.K=PSA.K*LOGN(PSA.K)                                       67, A
    SAQ      - QUANTUM FOR SAPLINGS (DIMENSIONLESS)
    PSA      - PROPORTION OF TOTAL AREA IN SAPLING HABITAT
                  (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

P6Q.K=PP6.K*LOGN(PP6.K)                                       68, A
    P6Q      - QUANTUM FOR POLE-6 HABITAT (DIMENSIONLESS)
    PP6      - PROPORTION OF TOTAL AREA IN POLE SIX
                  HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

P8Q.K=PP8.K*LOGN(PP8.K)                                       69, A
    P8Q      - QUANTUM FOR POLE-8 HABITAT (DIMENSIONLESS)
    PP8      - PROPORTION OF TOTAL AREA IN POLE EIGHT
                  HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM
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P1Q.K=PP1.K*LOGN(PP1.K)                                70. A
    P1Q      - QUANTUM FOR POLE-1 HABITAT (DIMENSIONLESS)
    PP1      - PROPORTION OF TOTAL AREA IN POLE TEN
                 HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

MTQ.K=PMT.K*LOGN(PMT.K)                                71. A
    MTQ      - QUANTUM FOR MATURE TIMBER HABITAT
                 (DIMENSIONLESS)
    PMT      - PROPORTION OF TOTAL AREA IN MATURE TIMBER
                 HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

OGQ.K=POG.K*LOGN(POG.K)                                72. A
    OGQ      - QUANTUM FOR OLD GROWTH HABITAT
                 (DIMENSIONLESS)
    POG      - PROPORTION OF TOTAL AREA IN OLD GROWTH
                 HABITAT (PERCENT)
    LOGN     - FUNCTION COMPUTES NATURAL LOGARITHM

WYI.K=WY.K/(BIVY.K*MSWI)                               73. A
MSWI=.417                                              73.1. C
    WYI      - WATER YIELD INDEX (DIMENSIONLESS)
    WY       - ANNUAL INCREASE IN WATER FROM ENTIRE FOREST
                 (ACRE FEET/YEAR)
    BIVY     - SPECIFIC NAME OF A FOREST TYPE
    MSWI     - MAXIMUM SUSTAINABLE WATER YIELD (ACRE FEET/
                 ACRE/YEAR)

WY.K=(SEWI*SED.K)+(SAWI*SAP.K)                         74. A
SEWI=SEW/DSE                                           74.1. N
SEW=TABHL(TWY,DSE,1,10,1)                              74.2. N
TWY=.98/1.72/2.33/2.84/3.28/3.65/3.97/4.24/4.48/       74.3. T
  4.68
SAWI=(SAWM-SEW)/DSA                                    74.4. N
SAWM=5.3                                               74.5. C
    WY       - ANNUAL INCREASE IN WATER FROM ENTIRE FOREST
                 (ACRE FEET/YEAR)
    SEWI     - WATER FROM SEEDLING HABITAT (ACRE FEET/
                 ACRE/YEAR)
    SED      - SEEDLING HABITAT (AREA)
    SAWI     - WATER FROM SAPLING HABITAT (ACRE FEET/ACRE/
                 YEAR)
    SAP      - SAPLING HABITAT (AREA)
    SEW      - WATER INCREASE, SEEDLING HABITAT, BY AGE
                 (ACRE FEET/ACRE/YEAR)
    DSE      - DELAY FOR BIVY TYPE SEEDLINGS (YEARS)
    TABHL    - FUNCTION,COMPUTES A VALUE FROM A TABLE
    TWY      - TABLE FOR WATER INCREASE BY AGE OF HABITAT
    SAWM     - MAXIMUM SUSTAINABLE INCREASE IN WATER (ACRE
                 FEET/ACRE/YEAR)
    DSA      - DELAY FOR BIVY TYPE SAPLINGS (YEARS)
  PROGRAM CONTROLS SECTOR

SPEC  DT=.25/LENGTH=170                                        74.8
    DT     - COMPUTATION INTERVAL (YEARS)
    LENGTH - TIME WHEN RUN IS TO BE TERMINATED

PRTPER.K=1+STEP(39,11)                                         75, A

PRINT     1)SED,SES/2)SAP,SAS/3)P6,P6S/4)P8,P8S/5)             75.1
  P1.P1S/6)MT,MTS/7)OG,OGS/
    SED      - SEEDLING HABITAT (AREA)
    SES      - BIVY TYPE SELL SEEDLINGS (AREA)
    SAP      - SAPLING HABITAT (AREA)
    SAS      - BIVY TYPE SELL SAPLINGS (AREA)
    P6       - POLE SIX HABITAT (AREA)
    P6S      - BIVY TYPE SELL POLE 6 (AREA)
    P8       - POLE EIGHT HABITAT (AREA)
    P8S      - BIVY TYPE SELL POLE 8 (AREA)
    P1       - POLE TEN HABITAT (AREA)
    P1S      - BIVY TYPE SELL POLE 10 (AREA)
    MT       - MATURE TIMBER HABITAT (AREA)
    MTS      - BIVY TYPE SELL MATURE TIMBER (AREA)
    OG       - OLD GROWTH HABITAT (AREA)
    OGS      - BIVY TYPE SELL OLD GROWTH (AREA)

PRINT     8)PTI,VT/9)PSE,PSA/10)PP6,POG/11)PSEA,               75.2
  PO8M/12)P1M,PMO/
    PTI      - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    VT       - TOTAL VOLUME OF TIMBER REMOVED FROM A
                 FOREST TYPE (VOLUME)
    PSE      - PROPORTION OF TOTAL AREA IN SEEDLING
                 HABITAT (PERCENT)
    PSA      - PROPORTION OF TOTAL AREA IN SAPLING HABITAT
                 (PERCENT)
    PP6      - PROPORTION OF TOTAL AREA IN POLE SIX
                 HABITAT (PERCENT)
    POG      - PROPORTION OF TOTAL AREA IN OLD GROWTH
                 HABITAT (PERCENT)
    PSEA     - PROPORTION OF TOTAL AREA IN SEEDLINGS AND
                 SAPLINGS (PERCENT)
    PO8M     - PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN
                 AND MATURE (PERCENT)
    P1M      - PROPORTION OF TOTAL AREA IN POLE TEN AND
                 MATURE (PERCENT)
    PMO      - PROPORTION OF TOTAL AREA IN MATURE AND OLD
                 GROWTH (PERCENT)

PRINT     13)BAL,OPM/14)OPS,WY                                 75.3
    BAL      - BALANCE IN CONTRASTING HEIGHTS OF TREES
    OPM      - OPENINGS PER SQUARE MILE (NUMBER)
    OPS      - OPENING SIZE DISTRIBUTION (AREA)
    WY       - ANNUAL INCREASE IN WATER FROM ENTIRE FOREST
                 (ACRE FEET/YEAR)

PLTPER.K=1+STEP(3,11)                                          76, A
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PLOT   PSE=S(0,.4)/PSA=A,PP6=6,PP8=8,PP1=1,PMT=M,      76.1
  POG=O(0,.8)
    PSE     - PROPORTION OF TOTAL AREA IN SEEDLING
                HABITAT (PERCENT)
    PSA     - PROPORTION OF TOTAL AREA IN SAPLING HABITAT
                (PERCENT)
    PP6     - PROPORTION OF TOTAL AREA IN POLE SIX
                HABITAT (PERCENT)
    POG     - PROPORTION OF TOTAL AREA IN OLD GROWTH
                HABITAT (PERCENT)

PLOT   PTI=T,SEMT=I,BEAR=B,GRS=G,TUR=K,BLU=L,DEER=D, 76.2
  SQU=Q,WYI=#(0,1)
    PTI     - POTENTIAL TIMBER INDEX (DIMENSIONLESS)
    SEMT    - SEDIMENT INDEX
    BEAR    - BEAR HABITAT INDEX
    GRS     - GROUSE HABITAT INDEX
    TUR     - TURKEY HABITAT INDEX
    BLU     - BLUEBIRD HABITAT INDEX
    DEER    - DEER HABITAT INDEX
    SQU     - SQUIRREL HABITAT INDEX
    WYI     - WATER YIELD INDEX (DIMENSIONLESS)

PLOT   VIS=V,UGL=U,OVN=O,PIL=P,FLIC=F,DON=N,TWE=W,     76.3
  PWE=E,HAR=H,CQ=*(0,1)
    UGL     - UGLINESS INDEX
    OVN     - OVEN BIRD HABITAT INDEX
    PIL     - PILEATED WOODPECKER HABITAT INDEX
    FLIC    - FLICKER WOODPECKER HABITAT INDEX
    DON     - DOWNEY WOODPECKER HABITAT INDEX
    TWE     - TOWHEE TYPE BIRD HABITAT
    PWE     - PEWEE HABITAT INDEX (DIMENSIONLESS)
    HAR     - HAIRY WOODPECKER HABITAT INDEX
    CQ      - CONSTRAINT QUANTUM (DIMENSIONLESS)
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ANALYTIC SILVICULTURE CONTROLS

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HSE=0/HSA=0/HP6=0/HP8=0/HP1=0/HMT=0/HOG=0/ISO=0/     76.6, C
  ISD=0
SEF=0/SAF=0/P6F=0/P8F=0/P1F=0/MTF=0/OGF=0            76.7, C
    HSA     - AGE SPECIFIED FOR HARVESTING BIVY SAPLINGS
                (YEARS)
    HP6     - AGE SPECIFIED FOR HARVESTING BIVY POLE 6
                (YEARS)
    HP8     - AGE SPECIFIED FOR HARVESTING BIVY POLE 8
                (YEARS)
    HP1     - AGE SPECIFIED FOR HARVESTING BIVY POLE 10
                (YEARS)
    HMT     - AGE SPECIFIED FOR HARVESTING BIVY MATURE
                TIMBER (YEARS)
    HOG     - AGE SPECIFIED FOR HARVESTING BIVY OLD
                GROWTH (YEARS)
    ISO     - INITIAL SIZE OF OPENINGS (AREA)
    ISD     - INITIAL STANDARD DEVIATION OF SIZE OF
                OPENINGS (AREA)
    SEF     - FRACTION OF BIVY TYPE HARVESTED AS SEEDLING
                HABITAT
    SAF     - FRACTION OF BIVY TYPE HARVESTED AS SAPLING
                HABITAT
    P6F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-6
                HABITAT
    P8F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-8
                HABITAT
    P1F     - FRACTION OF BIVY TYPE HARVESTED AS POLE-10
                HABITAT
    MTF     - FRACTION OF BIVY TYPE HARVESTED AS MATURE
                TIMBER HABITAT
    OGF     - FRACTION OF BIVY TYPE HARVESTED AS OLD
                GROWTH HABITAT
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APPENDIX C

AN ALPHABETICAL LIST OF VARIABLES, NUMBER AND TYPE OF EQUATION WHERE FIRST USED, DEFINITIONS AND UNITS OF MEASURE

NAME	NO	T	DEFINITION
A	11	A	AREA FOR HABITAT 'A' (AREA)
AGE			YOUNGEST AGE OF A SPECIFIED HABITAT (YEARS)
B	12	A	AREA FOR HABITAT 'B' (AREA)
BAL	30	A	BALANCE IN CONTRASTING HEIGHTS OF TREES
BBH	57	A	BLUEBIRD FEEDING AND NESTING HABITAT
BBO	58	A	SIZE OF OPENINGS FOR BLUEBIRDS
BDT	46	A	BEAR HABITAT DUE TO DENS IN OLD GROWTH
BEAR	45	A	BEAR HABITAT INDEX
BHMT	48	A	BEAR HABITAT DUE TO HARD MAST
BIVY	2	A	SPECIFIC NAME OF A FOREST TYPE
BLU	56	A	BLUEBIRD HABITAT INDEX
BSMT	47	A	BEAR HABITAT DUE TO SOFT MAST
C	13	A	AREA FOR HABITAT 'C' (AREA)
CA			CONVERSION OF LAND TO HABITAT 'A' (AREA)
CB			CONVERSION OF LAND TO HABITAT 'B' (AREA)
CC			CONVERSION OF LAND TO HABITAT 'C' (AREA)
CD			CONVERSION OF LAND TO HABITAT 'D' (AREA)
CE			CONVERSION OF LAND TO HABITAT 'E' (AREA)
CF			CONVERSION OF LAND TO HABITAT 'F' (AREA)
CG			CONVERSION OF LAND TO HABITAT 'G' (AREA)
CMT	8	A	CONVERSION OF LAND TO BIVY TYPE AS MATURE TIMBER (AREA)
COG	9	A	CONVERSION OF LAND TO BIVY TYPE AS OLD GROWTH (AREA)
CP1	7	A	CONVERSION OF LAND TO BIVY TYPE AS POLE 10 (AREA)
CP6	5	A	CONVERSION OF LAND TO BIVY TYPE AS POLE 6 (AREA)
CP8	6	A	CONVERSION OF LAND TO BIVY TYPE AS POLE 8 (AREA)
CQ	64	A	CONSTRAINT QUANTUM (DIMENSIONLESS)
CSA	4	A	CONVERSION OF LAND TO BIVY TYPE AS SAPLINGS (AREA)
CSE	3	A	CONVERSION OF LAND TO BIVY TYPE AS SEEDLINGS (AREA)
D	14	A	AREA FOR HABITAT 'D' (AREA)
DA			DELAY FOR HABITAT 'A' (YEARS)
DB			DELAY FOR HABITAT 'B' (YEARS)
DC			DELAY FOR HABITAT 'C' (YEARS)
DD			DELAY FOR HABITAT 'D' (YEARS)
DE			DELAY FOR HABITAT 'E' (YEARS)
DEER	32	A	DEER HABITAT INDEX
DF			DELAY FOR HABITAT 'F' (YEARS)
DC			DELAY FOR HABITAT 'G' (YEARS)
DLY			DELAY IN FLOW,SUCCESSION,FOR A SPECIFIED HABITAT (YEARS)
DMA	35	A	DEER HABITAT DUE TO HARD MAST
DMT			DELAY FOR BIVY TYPE MATURE TIMBER (YEARS)
DOG			DELAY FOR BIVY TYPE OLD GROWTH (YEARS)
DON	51	A	DOWNEY WOODPECKER HABITAT INDEX
DP1			DELAY FOR BIVY TYPE POLE 10 (YEARS)
DP6			DELAY FOR BIVY TYPE POLE 6 (YEARS)

DP8			DELAY FOR BIVY TYPE POLE 8 (YEARS)
DRT			DELAY FOR SALE AND REMOVAL OF TIMBER (YEARS)
DSA			DELAY FOR BIVY TYPE SAPLINGS (YEARS)
DSE	9.2	C	DELAY FOR BIVY TYPE SEEDLINGS (YEARS)
DT			COMPUTATION INTERVAL (YEARS)
E	15	A	AREA FOR HABITAT 'E' (AREA)
F	16	A	AREA FOR HABITAT 'F' (AREA)
FA			FRACTION OF TYPE DIVERTED FROM HABITAT 'A' (PERCENT)
FB			FRACTION OF TYPE DIVERTED FROM HABITAT 'B' (PERCENT)
FC			FRACTION OF TYPE DIVERTED FROM HABITAT 'C' (PERCENT)
FD			FRACTION OF TYPE DIVERTED FROM HABITAT 'D' (PERCENT)
FDH			FLOW OF ALL DIVERTED HABITATS (AREA/YEAR)
FE			FRACTION OF TYPE DIVERTED FROM HABITAT 'E' (PERCENT)
FF			FRACTION OF TYPE DIVERTED FROM HABITAT 'F' (PERCENT)
FG			FRACTION OF TYPE DIVERTED FROM HABITAT 'G' (PERCENT)
FIFGE			FUNCTION,SELECTS FIRST IF THIRD EQUALS, EXCEEDS THE FOURTH
FIFZE			FUNCTION,SELECTS FIRST IF THIRD EQUALS ZERO
FL			FLOW OF A SPECIFIED HABITAT (AREA/YEAR)
FLF	53	A	FLICKER HABITAT DUE TO OPEN FEEDING AREAS
FLIC	52	A	FLICKER WOODPECKER HABITAT INDEX
FLN	54	A	FLICKER NESTING AREAS
FLO	55	A	SIZE OF OPENING FOR FLICKER FEEDING
FOH			FLOW OF ALL HABITATS OLDER THAN THE SPECIFIED (AREA/YEAR)
G	17	A	AREA FOR HABITAT 'G' (AREA)
GRH	43	A	GROUSE HABITAT DUE TO POLE SIZED STANDS
GRO	44	A	GROUSE HABITAT DUE TO SIZE OF OPENINGS
GRS	42	A	GROUSE HABITAT INDEX
HA			HARVEST AGE DESIRED FOR HABITAT 'A' (YEARS)
HAG			HARVEST AGE DESIRED FOR A HABITAT (YEARS)
HAR	50	A	HAIRY WOODPECKER HABITAT INDEX
HB			HARVEST AGE DESIRED FOR HABITAT 'B' (YEARS)
HBTOB	13	A	MACRO FOR COMPUTING AREA OF A SPECIFIED HABITAT (AREA)
HC			HARVEST AGE DESIRED FOR HABITAT 'C' (YEARS)
HD			HARVEST AGE DESIRED FOR HABITAT 'D' (YEARS)
HE			HARVEST AGE DESIRED FOR HABITAT 'E' (YEARS)
HF			HARVEST AGE DESIRED FOR HABITAT 'F' (YEARS)
HG			HARVEST AGE DESIRED FOR HABITAT 'G' (YEARS)
HMT			AGE SPECIFIED FOR HARVESTING BIVY MATURE TIMBER (YEARS)
HOG			AGE SPECIFIED FOR HARVESTING BIVY OLD GROWTH (YEARS)
HP1			AGE SPECIFIED FOR HARVESTING BIVY POLE 10 (YEARS)
HP6			AGE SPECIFIED FOR HARVESTING BIVY POLE 6 (YEARS)
HP8			AGE SPECIFIED FOR HARVESTING BIVY POLE 8 (YEARS)

HSA	76.6	C	AGE SPECIFIED FOR HARVESTING BIVY SAPLINGS (YEARS)
HSE			AGE SPECIFIED FOR HARVESTING BIVY SEEDLINGS (YEARS)
HTD	33	A	DEER HABITAT DUE TO SEEDLINGS
IA			INITIAL AREA FOR HABITAT 'A' (AREA)
IB			INITIAL AREA FOR HABITAT 'B' (AREA)
IC			INITIAL AREA FOR HABITAT 'C' (AREA)
ID			INITIAL AREA FOR HABITAT 'D' (AREA)
IE			INITIAL AREA FOR HABITAT 'E' (AREA)
IF			INITIAL AREA FOR HABITAT 'F' (AREA)
IG			INITIAL AREA FOR HABITAT 'G' (AREA)
IMT			INVENTORY FOR BIVY TYPE MATURE TIMBER (AREA)
INV			INITIAL INVENTORY OF A SPECIFIED HABITAT (AREA)
IOG			INVENTORY FOR BIVY TYPE OLD GROWTH (AREA)
IP1			INVENTORY FOR BIVY TYPE POLE 10 (AREA)
IP6			INVENTORY FOR BIVY TYPE POLE 6 (AREA)
IP8			INVENTORY FOR BIVY TYPE POLE 8 (AREA)
ISA			INVENTORY FOR BIVY TYPE SAPLINGS (AREA)
ISD			INITIAL STANDARD DEVIATION OF SIZE OF OPENINGS (AREA)
ISE	9.1	C	INVENTORY FOR BIVY TYPE SEEDLINGS (AREA)
ISO			INITIAL SIZE OF OPENINGS (AREA)
LENGTH			TIME WHEN RUN IS TO BE TERMINATED
LOGN			FUNCTION COMPUTES NATURAL LOGARITHM
MACRO			INDICATES A FUNCTION COMPOSED OF ONE OR MORE EQUATIONS
MAX			FUNCTION SELECTS MAXIMUM VALUE
MEND			INDICATES THE END OF A SPECIFIED MACRO FUNCTION
MIN			FUNCTION,SELECTS MINIMUM VALUE
MSWI	73.1	C	MAXIMUM SUSTAINABLE WATER YIELD (ACRE FEET/ACRE/YEAR)
MT			MATURE TIMBER HABITAT (AREA)
MTF			FRACTION OF BIVY TYPE HARVESTED AS MATURE TIMBER HABITAT
MTQ	71	A	QUANTUM FOR MATURE TIMBER HABITAT (DIMENSIONLESS)
MTS			BIVY TYPE SELL MATURE TIMBER (AREA)
NH	64.2	C	NUMBER OF HABITAT CLASSES
NHQ	64.1	N	MAXIMUM CONSTRAINT FOR NUMBER OF HABITATS (DIMENSIONLESS)
NO	17	A	NUMBER OF OPENINGS FOR A PARTICULAR HABITAT (AREA)
NOP			NUMBER OF OPENINGS
NORMRN			FUNCTION FOR RANDOM NUMBERS NORMALLY DISTRIBUTED
NS	1.2	C	NULL STANDARD,EQUALS ZERO
OBTAH	1 1.1	L N	MACRO FOR COMPUTING AREA OF A SPECIFIED FOREST TYPE(AREA)
OG			OLD GROWTH HABITAT (AREA)

OGF			FRACTION OF BIVY TYPE HARVESTED AS OLD GROWTH HABITAT
OGQ	72	A	QUANTUM FOR OLD GROWTH HABITAT (DIMENSIONLESS)
OGS			BIVY TYPE SELL OLD GROWTH (AREA)
OPM	21	A	OPENINGS PER SQUARE MILE (NUMBER)
OPS			OPENING SIZE DISTRIBUTION (AREA)
OTD	34	A	DEER HABITAT DUE TO OPENING SIZE
OVN	59	A	OVEN BIRD HABITAT INDEX
PIL	49	A	PILEATED WOODPECKER HABITAT INDEX
PLTPER	76	A	
PMC	20	A	PROPORTION OF TOTAL AREA IN MATURE AND OLD GROWTH (PERCENT)
PMT	15	A	PROPORTION OF TOTAL AREA IN MATURE TIMBER HABITAT (PERCENT)
POG	16	A	PROPORTION OF TOTAL AREA IN OLD GROWTH HABITAT (PERCENT)
POBM	18	A	PROPORTION OF TOTAL AREA IN POLE EIGHT,TEN AND MATURE (PERCENT)
PP1	14	A	PROPORTION OF TOTAL AREA IN POLE TEN HABITAT (PERCENT)
PP6	12	A	PROPORTION OF TOTAL AREA IN POLE SIX HABITAT (PERCENT)
PP8	13	A	PROPORTION CF TOTAL AREA IN POLE EIGHT HABITAT (PERCENT)
PRS			PREVIOUS SALES FROM ALL OLDER HABITATS (AREA)
PRTPER	75	A	
PSA	11	A	PROPORTION OF TOTAL AREA IN SAPLING HABITAT (PERCENT)
PSE	10	A	PROPORTION OF TOTAL AREA IN SEEDLING HABITAT (PERCENT)
PSEA	17	A	PROPORTION OF TOTAL AREA IN SEEDLINGS AND SAPLINGS (PERCENT)
PSTV	1	A	FUNCTION ENSURES A POSITIVE VALUE
PTI	45	A	POTENTIAL TIMBER INDEX (DIMENSIONLESS)
PWE	63	A	PEWEE HABITAT INDEX (DIMENSIONLESS)
P1			POLE TEN HABITAT (AREA)
P1F			FRACTION OF BIVY TYPE HARVESTED AS POLE-10 HABITAT
P1M	19	A	PROPORTION OF TOTAL AREA IN POLE TEN AND MATURE (PERCENT)
P1Q	70	A	QUANTUM FOR POLE-1 HABITAT (DIMENSIONLESS)
P1S			BIVY TYPE SELL POLE 10 (AREA)
P6			POLE SIX HABITAT (AREA)
P6F			FRACTION OF BIVY TYPE HARVESTED AS POLE-6 HABITAT
P6Q	68	A	QUANTUM FOR POLE-6 HABITAT (DIMENSIONLESS)
P6S			BIVY TYPE SELL POLE 6 (AREA)
P8			POLE EIGHT HABITAT (AREA)
P8F			FRACTION OF BIVY TYPE HARVESTED AS POLE-8 HABITAT
P8Q	69	A	QUANTUM FOR POLE-8 HABITAT (DIMENSIONLESS)
P8S			BIVY TYPE SELL POLE 8 (AREA)
REF			REFORESTATION RATE (PERCENT)
RML	1	R	AMOUNT OF A HABITAT REMOVED BY HARVEST (AREA)

SA			AMOUNT OF HABITAT 'A' TO SELL (AREA)
SAF			FRACTION OF BIVY TYPE HARVESTED AS SAPLING HABITAT
SAP			SAPLING HABITAT (AREA)
SAQ	67	A	QUANTUM FOR SAPLINGS (DIMENSIONLESS)
SAS			BIVY TYPE SELL SAPLINGS (AREA)
SAWI	74.4	N	WATER FROM SAPLING HABITAT (ACRE FEET/ACRE/YEAR)
SAWM	74.5	C	MAXIMUM SUSTAINABLE INCREASE IN WATER (ACRE FEET/ACRE/YEAR)
SB			AMOUNT OF HABITAT 'B' TO SELL (AREA)
SC			AMOUNT OF HABITAT 'C' TO SELL (AREA)
SD			AMOUNT OF HABITAT 'D' TO SELL (AREA)
SDT	38	A	SQUIRREL HABITAT DUE TO DEN TREES IN OLD GROWTH
SE			AMOUNT OF HABITAT 'E' TO SELL (AREA)
SED			SEEDLING HABITAT (AREA)
SEF	76.7	C	FRACTION OF BIVY TYPE HARVESTED AS SEEDLING HABITAT
SEL	3	R	AMOUNT OF A HABITAT TO SELL (AREA)
SEMT	22	A	SEDIMENT INDEX
SEQ	66	A	QUANTUM FOR SEEDLINGS (DIMENSIONLESS)
SES			BIVY TYPE SELL SEEDLINGS (AREA)
SEW	74.2	N	WATER INCREASE, SEEDLING HABITAT, BY AGE (ACRE FEET/ACRE/YEAR)
SEWI	74.1	N	WATER FROM SEEDLING HABITAT (ACRE FEET/ACRE/YEAR)
SF			AMOUNT OF HABITAT 'F' TO SELL (AREA)
SG			AMOUNT OF HABITAT 'G' TO SELL (AREA)
SO			SIZE OF OPENING (AREA)
SOH	16	A	SIZE OF OPENING FOR PARTICULAR HABITAT (AREA)
SQU	36	A	SQUIRREL HABITAT INDEX
TABHL			FUNCTION.COMPUTES A VALUE FROM A TABLE
TBBH	57.1	T	TABLE BLUEBIRD HABITAT DUE TO SEEDINGS
TBBO	58.1	T	TABLE SIZE OF OPENINGS FOR BLUEBIRDS
TBDT	46.1	T	TABLE BEAR DENS IN OLD GROWTH
TBHM	48.1	T	TABLE BEAR HABITAT DUE TO HARD MAST
TBSM	47.1	T	TABLE BEAR HABITAT DUE TO SOFT MAST
TDMA	35.1	T	TABLE DEER HABITAT DUE TO HARD MAST
TDCN	51.1	T	TABLE DOWNEY WOODPECKER HABITAT
TFLF	53.1	T	TABLE FLICKER OPEN FEEDING AREAS
TFLN	54.1	T	TABLE FLICKER NESTING AREAS
TFLO	55.1	T	TABLE OPENING SIZE FOR FLICKER FEEDING
TGRF	43.1	T	TABLE GROUSE HABITAT DUE TO POLE STANDS
TGRC	44.1	T	TABLE GROUSE HABITAT DUE TO SIZE OF OPENINGS
THAF	50.1	T	TABLE HAIRY WOODPECKER HABITAT
THS	37	A	SQUIRREL HABITAT DUE TO HARD MAST
THTD	33.1	T	TABLE DEER HABITAT DUE TO SEEDLINGS
TIN			AREA TRANSFERRED INTO A HABITAT (AREA)
TMR	9.7	C	TIMBER ROTATION FOR MAXIMUM YIELD (YEARS)
TNH	48	A	TOTAL NUMBER OF OPENINGS FOR A TYPE

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TCFM         1.1 T  TABLE FOR OPENING FACTOR MODIFICATION
                       (DIMENSIONLESS)
TCID        34.1 T  TABLE DEER HABITAT DUE TO OPENING SIZE
TOU         11   R  TRANSFER OUT OF A HABITAT BY SUCCESSION
                       (AREA/YEAR)
TOVN        59.1 T  OVEN BIRD TYPE HABITAT
TPIL        49.1 T  TABLE PILEATED HABITAT DUE TO OLD GROWTH
TPWE        63.1 T  TABLE PEWEE HABITAT
TQ          65   A  TOTAL QUANTUM FOR HABITATS (DIMENSIONLESS)
TSDT        38.1 T  TABLE SQUIRREL HABITAT DUE TO OLD GROWTH
TSFMT       22.1 T  SEDIMENT TABLE
TSLF         1   T  TABLE FOR SELL FRACTIONS (DIMENSIONLESS)
TT                  TOTAL TRANSFER TO A FOREST TYPE
TTHS        37.1 T  TABLE SQUIRREL HABITAT DUE TO HARD MAST
TTFC        41.1 T  TABLE TURKEY HABITAT DUE TO OPENING SIZE
TTRT        40.1 T  TABLE TURKEY HABITAT DUE TO HARD MAST
TTWE        61.1 T  TABLE TOWHEE TYPE HABITAT
TTWO        62.1 T  TABLE FOR OPENING SIZE FOR TOWHEE TYPE
                       BIRDS
TTYI         9.3 T  TABLE FOR TIMBER VOLUME FACTOR (VOLUME
                       UNITS/UNIT AREA)
TUGN        25.1 T  TABLE UGLY DUE TO OPENING FREQUENCY
TUGO        26.1 T  TABLE UGLY DUE TO OPENING SIZE
TUGS        24.1 T  TABLE, UGLINESS DUE TO SEEDLINGS
TUR         39   A  TURKEY HABITAT INDEX
TURO        41   A  TURKEY HABITAT DUE TO SIZE OF OPENINGS
TURT        40   A  TURKEY HABITAT DUE TO HARD MAST
TVBA        29.1 T  TABLE VISUAL DUE TO BALANCE
TVPO        31.1 T  TABLE VISUAL DUE TO OLD GROWTH
TVSE        28.1 T  TABLE VISUAL DUE TO SEEDLINGS
TWE         60   A  TOWHEE TYPE BIRD HABITAT
TWH         61   A  TOWHEE TYPE HABITAT DUE TO SAPLINGS
TWO         62   A  OPENING SIZE FOR TOWHEE TYPE HABITAT
TWY         74.3 T  TABLE FOR WATER INCREASE BY AGE OF HABITAT
UGL         23   A  UGLINESS INDEX
UGN         25   A  UGLINESS DUE TO FREQUENCY OF OPENINGS
UGO         26   A  UGLY DUE TO OPENING SIZE
UGS         24   A  UGLY DUE TO SEEDLING HABITAT
UNTY         1   A  FUNCTION ENSURES A VALUE EQUAL TO OR
                       GREATER THAN ONE
VBAL        29   A  VISUAL DUE TO BALANCE
VIS         27   A  VISUAL INDEX
VPOG        31   A  VISUAL DUE TO OLD GROWTH
VRM         14   A  VOLUME OF TIMBER REMOVED BY HARVEST
                       (VOLUME/YEAR)
VSE         28   A  CONTRIBUTION OF SEEDLINGS TO VISUAL APPEAL
VT          46   A  TOTAL VOLUME OF TIMBER REMOVED FROM A
                       FOREST TYPE (VOLUME)
WOH         49   A  WEIGHTED OPENING SIZE FOR A TYPE
WY          74   A  ANNUAL INCREASE IN WATER FROM ENTIRE FOREST
                       (ACRE FEET/YEAR)
WYI         73   A  WATER YIELD INDEX (DIMENSIONLESS)
X                   VALUE TO BE ACTED ON BY FUNCTIONS PSTV,
                       UNTY,ZERO
YST          9.6 C  YIELD OF TIMBER AT OPTIMUM ROTATION (CUBIC
                       VOLUME/ACRE)
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ZERO	1	A	FUNCTION ENSURES A VALUE EQUAL TO OR GREATER THAN ZERO
$AA	43.1	N	YOUNGEST AGE OF HABITAT 'A' (YEARS)
$AB	43.2	N	YOUNGEST AGE OF HABITAT 'B' (YEARS)
$AC	43.3	N	YOUNGEST AGE OF HABITAT 'C' (YEARS)
$AD	43.4	N	YOUNGEST AGE OF HABITAT 'D' (YEARS)
$AE	43.5	N	YOUNGEST AGE OF HABITAT 'E' (YEARS)
$AF	43.6	N	YOUNGEST AGE OF HABITAT 'F' (YEARS)
$AG	43.7	N	YOUNGEST AGE OF HABITAT 'G' (YEARS)
$AHA	14.2	N	ACTUAL HARVEST AGE (YEARS)
$AS	2	L	ACCUMULATED SALES FOR A HABITAT (AREA)
	2.1	N	
$CA			CONVERSION OF LAND TO HABITAT 'A' (AREA)
$CON	2	R	AMOUNT OF LAND CONVERTED TO A FOREST TYPE
$CV	9	A	COVERAGE OF RESERVES FOR A HABITAT (DIMENSIONLESS)
$EQ	10	A	EQUILIBRIUM RESERVES FOR SALES (AREA)
$FAO	38	A	FLOW OF HABITAT 'A' AND OLDER (AREA/YEAR)
$FBO	39	A	FLOW OF HABITAT 'B' AND OLDER (AREA/YEAR)
$FCO	40	A	FLOW OF HABITAT 'C' AND OLDER (AREA/YEAR)
$FDO	41	A	FLOW OF HABITAT 'D' AND OLDER (AREA/YEAR)
$FEO	42	A	FLOW OF HABITAT 'E' AND OLDER (AREA/YEAR)
$FFO	43	A	FLOW OF HABITAT 'F' AND OLDER (AREA/YEAR)
$FLA	31	A	FLOW OF HABITAT 'A' (AREA/YEAR)
$FLB	32	A	FLOW OF HABITAT 'B' (AREA/YEAR)
$FLC	33	A	FLOW OF HABITAT 'C' (AREA/YEAR)
$FLD	34	A	FLOW OF HABITAT 'D' (AREA/YEAR)
$FLE	35	A	FLOW OF HABITAT 'E' (AREA/YEAR)
$FLF	37	A	FLOW OF HABITAT 'F' (AREA/YEAR)
$FLG	36	A	FLOW OF HABITAT 'G' (AREA/YEAR)
$HRN	6	A	HARVEST REQUIRED FROM A HABITAT (AREA/YEAR)
$LQ	4	A	LIQUIDATE RESERVES OF A HABITAT (AREA/YEAR)
$NOA			NUMBER OF OPENINGS FOR HABITAT 'A'
$NOB			NUMBER OF OPENINGS FOR HABITAT 'B'
$NOC			NUMBER OF OPENINGS FOR HABITAT 'C'
$NOD			NUMBER OF OPENINGS FOR HABITAT 'D'
$NOE			NUMBER OF OPENINGS FOR HABITAT 'E'
$NOF			NUMBER OF OPENINGS FOR HABITAT 'F'
$NOG			NUMBER OF OPENINGS FOR HABITAT 'G'
$OA	50	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'A' (AREA)
$OB	51	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'B' (AREA)
$OC	52	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'C' (AREA)
$OD	53	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'D' (AREA)
$OE	54	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'E' (AREA)
$OF	55	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'F' (AREA)
$OG	56	A	OPENING SIZE DISTRIBUTION FOR HABITAT 'G' (AREA)
$R	19	A	TOTAL AREA OF A TYPE REMOVED BY HARVEST (AREA)

```
$RA                AREA OF HABITAT 'A' REMOVED BY HARVEST
                     (AREA)
$RB                AREA OF HABITAT 'B' REMOVED BY HARVEST
                     (AREA)
$RC                AREA OF HABITAT 'C' REMOVED BY HARVEST
                     (AREA)
$RD                AREA OF HABITAT 'D' REMOVED BY HARVEST
                     (AREA)
$RE                AREA OF HABITAT 'E' REMOVED BY HARVEST
                     (AREA)
$REV       3    R  REVERSION OF LAND FROM A TYPE OF HABITAT
                     (AREA)
$RF                AREA OF HABITAT 'F' REMOVED BY HARVEST
                     (AREA)
$RG                AREA OF HABITAT 'G' REMOVED BY HARVEST
                     (AREA)
$RSR       5    L  RESERVE ACCUMULATION FOR A HABITAT (AREA)
           5.1  N
$RVA       4    A  REVERSION OF LAND FROM HABITAT 'A' (AREA)
$RVB       5    A  REVERSION OF LAND FROM HABITAT 'B' (AREA)
$RVC       6    A  REVERSION OF LAND FROM HABITAT 'C' (AREA)
$RVD       7    A  REVERSION OF LAND FROM HABITAT 'D' (AREA)
$RVE       8    A  REVERSION OF LAND FROM HABITAT 'E' (AREA)
$RVF       9    A  REVERSION OF LAND FROM HABITAT 'F' (AREA)
$RVG      10    A  REVERSION OF LAND FROM HABITAT 'G' (AREA)
$SBO      26    A  SALE OF HABITAT 'B' AND OLDER (AREA
$SCO      27    A  SALE OF HABITAT 'C' AND OLDER (AREA
$SDO      28    A  SALE OF HABITAT 'D' AND OLDER (AREA
$SDY       7    A  STEADY STATE SALES OF A HABITAT (AREA/YEAR)
$SELF      8    A  SELL FRACTION (DIMENSIONLESS)
$SEO      29    A  SALE OF HABITAT 'E' AND OLDER (AREA
$SFO      30    A  SALE OF HABITAT 'F' AND OLDER (AREA
$SO       44    A  SIZE OF OPENING (AREA)
$SOA               SIZE OF OPENINGS FOR HABITAT 'A'
$SOB               SIZE OF OPENINGS FOR HABITAT 'B'
$SOC               SIZE OF OPENINGS FOR HABITAT 'C'
$SOD               SIZE OF OPENINGS FOR HABITAT 'D'
$SOE               SIZE OF OPENINGS FOR HABITAT 'E'
$SOF      15    A  SIZE OF OPENING FACTOR (DIMENSIONLESS)
$SOG               SIZE OF OPENINGS FOR HABITAT 'G'
$SUR      12    A  SUCCESSION RESERVES (AREA)
$TA       18    R  TRANSFER LAND TO HABITAT 'A' (AREA)
$TB       20    R  TRANSFER LAND TO HABITAT 'B' (AREA)
$TC       21    R  TRANSFER LAND TO HABITAT 'C' (AREA)
$TD       22    R  TRANSFER LAND TO HABITAT 'D' (AREA)
$TE       23    R  TRANSFER LAND TO HABITAT 'E' (AREA)
$TF       24    R  TRANSFER LAND TO HABITAT 'F' (AREA)
$TFT               TRANSFER FROM A TYPE (AREA)
$TG       25    R  TRANSFER LAND TO HABITAT 'G' (AREA)
$TIH               TOTAL AREA INITIAL HABITATS FOR A FOREST
                     TYPE (AREA)
$TIM      47    A  TIMBER MAXIMUM YIELD FOR OPTIMUM ROTATION
                     (VOLUME)
$TOA               TRANSFER AREA OUT OF HABITAT 'A'
$TOB               TRANSFER AREA OUT OF HABITAT 'B'
$TOC               TRANSFER AREA OUT OF HABITAT 'C'
$TOD               TRANSFER AREA OUT OF HABITAT 'D'
$TOE               TRANSFER AREA OUT OF HABITAT 'E'
```

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$TOF                 TRANSFER AREA OUT OF HABITAT 'F'
$TOG                 TRANSFER AREA OUT OF HABITAT 'G'
$TYI      47.1 N     TIMBER YIELD INDEX FOR OPTIMUM ROTATION
                       (DIMENSIONLESS)
$VA                  VOLUME OF TIMBER REMOVED FROM HABITAT 'A'
$VB                  VOLUME OF TIMBER REMOVED FROM HABITAT 'B'
$VC                  VOLUME OF TIMBER REMOVED FROM HABITAT 'C'
$VD                  VOLUME OF TIMBER REMOVED FROM HABITAT 'D'
$VE                  VOLUME OF TIMBER REMOVED FROM HABITAT 'E'
$VF                  VOLUME OF TIMBER REMOVED FROM HABITAT 'F'
$VG                  VOLUME OF TIMBER REMOVED FROM HABITAT 'G'
$VU       14.1 N     VOLUME FACTOR FOR TIMBER (VOLUME UNITS/UNIT
                       AREA)
```

Boyce, Stephen G.
1980. Management of forests for optimal benefits (DYNAST-OB).
USDA For. Serv., Res. Pap. SE-204, 92 p. Southeast.
For. Exp. Stn., Asheville, N. C.

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Research Paper
SE-205

Flame Characteristics for Fires in Southern Fuels

by Ralph M. Nelson, Jr.

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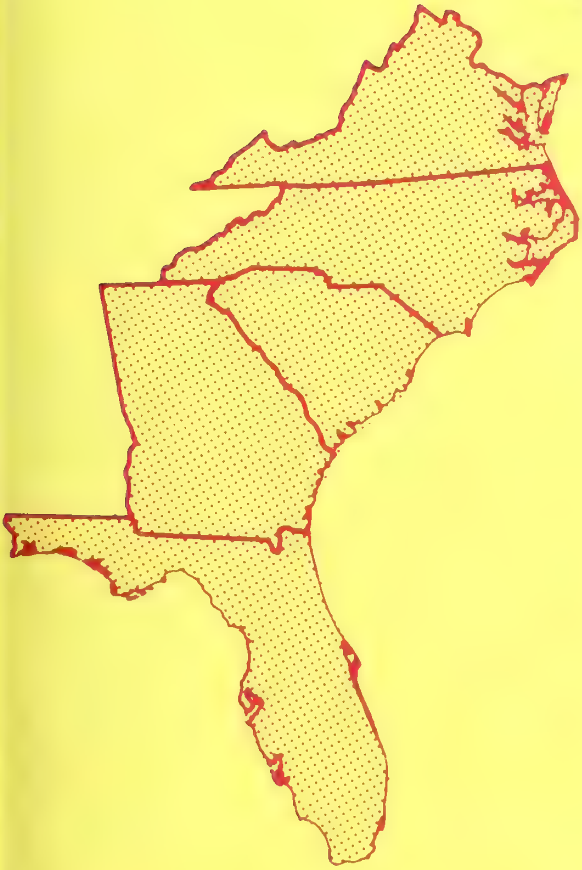

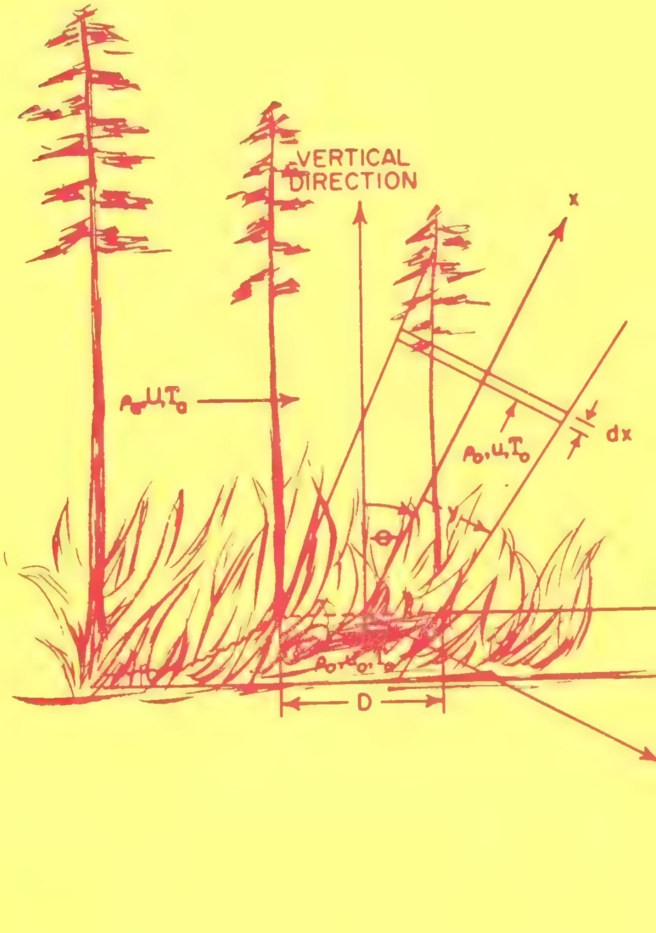

English units are still commonly used in forestry in the United States, and therefore are used in this paper. Conversion factors from English to metric units are:

From English	*Abbreviation*	*To metric*	*Multiply by*
Btu/pound	Btu/lb	joule/gram	2.3263
Btu/second/foot	Btu/ft-sec	kilowatt/meter	3.4613
Btu/second/foot^2	Btu/ft^2-sec	kilowatt/meter^2	11.3559
foot	ft	meter	.3048
foot^2	ft^2	meter^2	.0929
foot/second	ft/sec	meter/second	.3048
¼ milacre	—	meter^2	1.0117
pound	lb	kilogram	.4536
pound/foot^2	lb/ft^2	kilogram/meter^2	4.8818

June 1980
Southeastern Forest Experiment Station
Asheville, North Carolina

Flame Characteristics for Fires in Southern Fuels

by
Ralph M. Nelson, Jr., Mechanical Engineer
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ABSTRACT.—Equations describing flow in buoyant turbulent jets have been applied to the derivation of characteristics for forest fire flames. Approximate solutions are used to develop relationships for flame lengths, angles, heights, and tip velocities for fires heading with the wind and burning in calm air as functions of Byram's fire intensity, I (Btu/ft-sec). Flame length and velocity relationships are tested with data taken during controlled burns in southern fuels and with data from the literature. Backfire data are described by the equations for calm-air conditions. Both theoretical and experimental results show that flame lengths for backfires and headfires vary as $I^{2/3}$ and $I^{1/2}$, respectively; flame tip velocities vary as $I^{1/3}$ and $I^{1/2}$.

Keywords: Flame length, flame velocity, flame tilt, fire intensity, buoyant flames.

Through concentrated research during recent years, the U.S. Forest Service has developed a capability for predicting burning rates of surface fires in representative forest fuel types throughout the Nation. During these same years, there has been a growing demand from Federal and State land management agencies for better predictions of wild land fire behavior which would contribute to improved fire and smoke management planning. Thus, burning-rate predictions need to be used in the consideration of such problems as description of spotting, crowning, convection column rise, and fire effects. Because of increasing interest in such problems, research is becoming more sharply focused on flame characteristics and their role in fire behavior phenomena.

A few studies of flame characteristics in real fuels have been reported. Research has been carried out in southern fuels by Byram (1959), in logging slash of western fuels by Anderson and others (1966), and in western grasses by Sneeuwjagt and Frandsen (1977). Thomas (1971) and Van Wagner (1968) also have made flame measurements in field experiments.

Much past research on flame characteristics has been associated with analytical work and modeling efforts in the laboratory. Among the variables studied are flame length, flame tip velocity, and angle of flame tilt. However, prediction models of these and other characteristics have not been firmly established with field experiments.

Flame lengths for line fires have been studied by Thomas (1963), Fons and others (1962), and Steward (1964) from theoretical and experimental points of view. For line fires in calm air, Thomas (1963) and Rothermel and Anderson (1966) have obtained empirical flame-length correlations of the form

$$L/D = K\left[\frac{m''}{\rho_o\sqrt{gD}}\right]^n$$

with the exponent n taking on values close to two-thirds. In this relation L is flame length, D is flame depth, m'' is rate of fuel consumption per unit area, ρ_0 is mass density of the ambient air, g is acceleration due to gravity and K is a constant that differs among fuel species. The data of Rothermel and Anderson (1966) for fires in calm air and wind were analyzed in a different way and reported by Anderson and Rothermel (1965). The general form of the correlation equation was retained, but values of n were approximately equal to unity. In other experiments, Thomas (1971) has applied $n = 2/3$ to wind-driven fires in the field with reasonable success.

The information now available indicates that different equations describe the variation in flame lengths, depending on the range in experimental data and other factors. Albini (1976) has pointed out that experimental flame-length data seem to be well described by an equation formulated by Byram (1959) (which corresponds approximately to $n = 1$), although there is more theoretical justification for Thomas' equation (for $n = 2/3$). The experimental studies of Sneeuwjagt and Frandsen (1977) also show that Byram's equation applies over a greater range of fire intensity than Thomas' equation.

In experiments on alcohol pool fires, Thomas (1965) found that flame tip velocities were proportional to the square root of the height of the flame zone. Theoretical flame velocities were reported by Byram and Nelson (1974). Flame tilt angles have been studied theoretically and in the laboratory by Anderson and Rothermel (1965), Welker and Sliepcevich (1966), and Fang (1969). Flame height—the perpendicular distance from the flame tip to the ground—has been discussed by Thomas and others (1963). The work on velocities, angles, and heights described above has produced several relationships among flame, fuel, and weather variables, none of which has been verified with field experiments in a convincing manner.

More field data are needed for testing current theories. Furthermore, a general analysis is needed from which information on flame characteristics of forest fires can be derived. To my knowledge, the only treatment of this kind is by Fang (1969) who derived flame length and tilt angle relationships from the theory of buoyant turbulent jets applied to a headfire in wind. However, he did not consider backfires and calm-air fires. The present paper is an attempt to extend this work. The flame model and analytical methods of Fang, modified in places, are used to derive flame lengths, heights, tip velocities, and angles of tilt for heading and calm-air fires. Expressions are obtained for flame lengths and velocities as functions of Byram's (1959) fire intensity by considering all other factors appearing in these expressions to be constant. Flame characteristics are written in terms of fire intensity for the purpose of providing a basis of comparison between the results of this paper and the existing models of Byram (1959) and Thomas (1963). Results of the analysis are used to develop relationships between lengths and velocities for headfires and backfires. The equations are compared with experimental data from fires of low intensity in southern fuels and with data in the literature. Expressions for flame tilt angle and flame height are developed also, but no comparisons with experimental data are made.

THEORETICAL CONSIDERATIONS

Equations for flame characteristics are derived for both headfires and calm-air fires. It is argued that flame lengths and velocities of backfires can be represented with the calm-air analysis.

Headfires

Following Fang (1969), we assume that combustion in the flame is controlled by the rate at which air mixes with volatilized fuel through the process of entrainment. In the case of headfires, possible accretion of horizontally moving air in the flame is not considered. The magnitude of the error built into the model through omission of terms accounting for this air is not known, but probably is small unless windspeed exceeds 15 to 20 miles per hour. The flame geometry is shown in figure 1, which depicts the cross section of a fire of infinite length (into the page) burning on flat ground. The x axis, an axis of symmetry through the center of the flame, makes an angle, Θ, with the vertical direction. This angle, which does not change with changing x, is caused by a mean wind of speed U, blowing from left to right. The quantities Θ and U are known to vary, but are taken as constants in accordance with Fang (1969). Such a formulation simplifies the mathematical solution and seems to be a reasonable first approach. Though in a fluctuating turbulent flow, the flame is considered to be in a quasi-steady state in surroundings of constant density, ρ_a, and absolute temperature, T_a. The quantities u and y vary with axial distance, x. They represent local axial velocity and half the transverse dimension, respectively. Thus, y at a given x is half the flame thickness in a direction perpendicular to the x

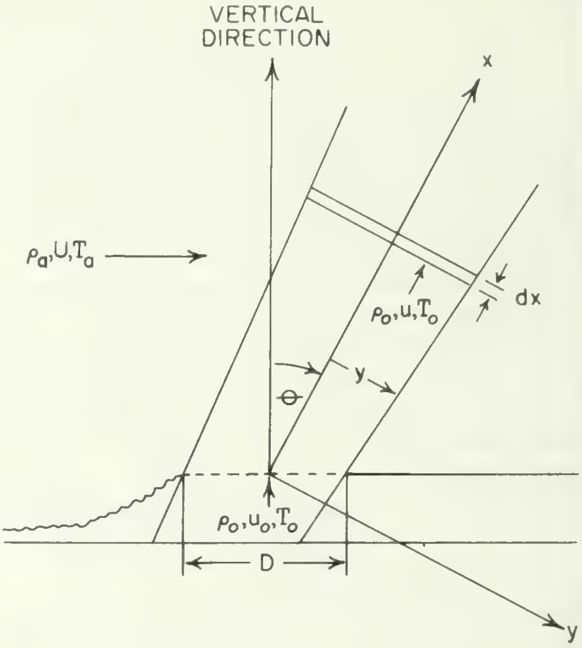

Figure 1.—Geometrical model of a line fire burning in wind.

axis. Flame depth, D, is defined as the distance from front to rear of the flame, measured at the fuel surface. Fuel pyrolysis and partial combustion occur beneath the surface due to heat feedback from the flame and entrainment of some air into the fuel layer. This air is completely utilized in combustion. Thus, a mixture of volatilized fuel and combustion products of density, ρ_o, and absolute temperature, T_o, flow perpendicularly through the surface at a mean velocity, u_o. The density and temperature are considered constant with x, which results in a simpler analysis than that of Fang's for variable density. At the visible flame tip, combustion is completed in the sense that the reacting gases pass from a flaming to nonflaming state. It is assumed that because of imperfect mixing, the air entrained into the visible flame exceeds the amount required for stoichiometric combustion. The entrainment process is taken to be independent of fire size, type, and behavior. Radiation loss is accounted for with a reduced heat of combustion. In addition, the following assumptions are taken from Fang (1969):

a. Turbulent flow is fully developed and molecular transport processes are insignificant.

b. The flame behaves as a buoyant turbulent jet in which the rate of air entrainment is proportional to the local axial velocity.

c. The distribution of velocity is constant across the jet axis.

d. All flame components obey the ideal gas law and possess thermal properties that equal those of air and are independent of temperature.

e. Upon mixing, the volatilized fuel and entrained air react instantaneously in stoichiometric proportions.

The equations describing the system are written by considering conservation of mass and momentum for the elemental flame volume of thickness, dx, in figure 1. These equations are:

$$\frac{d(uy)}{dx} = \left(\frac{\rho_a}{\rho_o}\right) E' u \qquad (1)$$

$$\frac{d(u^2 y)}{dx} = \frac{C_F}{4}\left(\frac{\rho_a}{\rho_o}\right) U^2 \cot\Theta \qquad (2)$$

where C_F is a flame drag coefficient and E' is a constant associated with entrainment of ambient air into one side of the flame. A transverse force balance applied to the elemental flame volume gives

$$\frac{\tan\Theta}{\cos\Theta} = \frac{C_F \rho_a U^2}{4gy(\rho_a - \rho_o)} \qquad (3)$$

in which g is acceleration due to gravity and Θ is constant. Equation (3), according to the assumptions of the model, is not strictly valid because it contains only one variable, y. In a thorough analysis, ρ_o and Θ would be replaced by variable quantities and the equation would be correct. It is assumed further that changes of y with x are sufficiently small that, to the level of accuracy required here, the equation $2y = D\cos\Theta$ can be regarded as roughly valid—not only at $x = 0$, but for all x. Thus, Equation (3) can be written approximately as

$$\tan\Theta = \frac{C_F \rho_a U^2}{2gD(\rho_a - \rho_o)}. \qquad (4)$$

Dimensionless variables are defined as

$$x' = \frac{x}{D},\ y' = \frac{2y}{D} = \cos\Theta,\ u' = \frac{u}{u_o}.$$

Equations (1) and (2) now can be written as

$$\frac{d(u'y')}{dx'} = Au' \qquad (5)$$

$$\frac{d(u'^2 y')}{dx'} = B \qquad (6)$$

where the constants A and B are obtained from Equations (1), (2), and (4) as

$$A = E\left(\frac{\rho_a}{\rho_o}\right)$$
$$B = \frac{gD(\rho_a - \rho_o)}{\rho_o u_o^2} \qquad (7)$$

and $E = 2E'$ is an entrainment constant for the entire flame.

Equations (5) to (7) can be used to develop expressions for flame length and other characteristics for headfires. Details of these derivations are presented in Appendix I. The final equations are:

Flame length:

$$L = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{I_R}{Eg(1 - \rho_o/\rho_a)}\right]^{1/2} I^{1/2} \qquad (8)$$

Flame tilt angle:

$$\tan \Theta = \frac{C_F U^2 I_R}{2gI(1 - \rho_o/\rho_a)} \tag{9}$$

Flame height:

$$h = L[1 + \tan^2\Theta]^{1/2} \tag{10}$$

Flame tip velocity:

$$u_L = \left[\frac{g}{EI_R}(1 - \rho_o/\rho_a)\right]^{1/2} I^{1/2} \tag{11}$$

In Equation (10), L and tan Θ are obtained from Equations (8) and (9). The previously undefined quantities in Equations (8) to (11) are:

r = mass of air entrained into the visible flame per mass of fuel burned, lb/lb

H = heat yield of the combustion process, Btu/lb

I_R = reaction intensity[1], Btu/ft²-sec

I = fire intensity[2], Btu/ft-sec.

Equations (8) and (11) imply a relationship between u_L and L. Elimination of $I^{1/2}$ yields

$$u_L = \left[\frac{5\rho_a Hg(1 - \rho_o/\rho_a)}{(r^2 + 6r + 5)I_R}\right]L. \tag{12}$$

If the factors multiplying L are roughly constant, u_L and L should be proportional. Of primary interest is the variability of I_R. The extent to which I_R changes for field burns in a given fuel or from one fuel type to another is unknown. The field data of Sneeuwjagt and Frandsen (1977) for headfires in grass indicate that I_R is a variable quantity. On the other hand, observations of wind- and slope-driven fires in the laboratory by Byram and others (1966) suggest that I_R may be affected by changes in windspeed and slope angle only to the extent that fuel consumption changes from one fire to another. For the sake of simplicity, I_R is considered constant from fire to fire within and among fuel types. This assumption is an oversimplification of the actual variation, and is believed to be a meaningful hypothesis only for fuel types in which unit area fuel consumption, fuel particle surface-to-volume ratio, and fuel moisture are not widely different. The experimental fires discussed later in this paper seem to satisfy these conditions reasonably well.

Calm-Air Fires

Forest fires burning on flat ground in very light winds or calm air exhibit vertical flames. Thus, in figure 1 the flame must be visualized as standing vertically with the y axis coincident with the fuel surface and Θ = 0. Spread rates and flame depths are smaller than for headfires because the primary mechanism of heat transfer is radiation rather than the combined effects of radiation and convection present in headfires. The assumptions discussed previously for headfires also apply to the mathematical description of calm-air fires. Because Θ is zero, Equation (4) is no longer required for description of the problem. Also, Equation (2) must be replaced by

$$\frac{d(u^2y)}{dx} = gy\frac{(\rho_a - \rho_o)}{\rho_o}. \tag{13}$$

The equations to be solved are expressed in dimensionless form as:

$$\frac{d(u'y')}{dx'} = Au' \tag{14}$$

$$\frac{d(u'^2y')}{dx'} = By' \tag{15}$$

where A and B are given by Equations (7). The analytical procedures used to obtain flame characteristics are the same as for headfires, and are given in Appendix II. Only flame length and tip velocity are considered, however, because Θ is known and flame length equals flame height for fires in calm air. Equations for these variables are:

Flame length: L =

$$\left\{\frac{9(r^2 + 10r + 25)\,[(r + 1)^{2/3} - 1]^3}{50H^2E^2\rho_a^2 g(\rho_a/\rho_o - 1)}\right\}^{1/3} I^{2/3} \tag{16}$$

Flame tip velocity: u_L =

$$\left[\frac{3(r^2 + 6r + 5)g(1 - \rho_o/\rho_a)}{20EH\rho_o}\right]^{1/3} I^{1/3} \tag{17}$$

A relationship between u_L and L can be obtained with elimination of $I^{2/3}$ between Equation

---

[1] Reaction intensity is the rate of heat release per unit area of ground below the combustion zone of a fire.

[2] Fire intensity, as defined by Byram (1959), for a spreading fire is the rate of heat release per unit length of fire front.

(16) and the square of Equation (17). Thus, u_L can be written in terms of L as

$$u_L = \left[\frac{17(r^2 + 6r + 5)}{48(r^2 + 10r + 25)^{1/2}}\right]^{1/3} \left\{\frac{g(\rho_a/\rho_o - 1)}{[(r+1)^{2/3} - 1]}\right\}^{1/2} L^{1/2} \tag{18}$$

for calm-air fires.

Backfires

A separate analysis for flame characteristics of backfires is not made because the results of previous analysis can be applied to these fires. Backfires on flat ground spread against the wind, and one might expect a modified form of the analysis for headfires to apply. However, in the section describing experimental measurements of flame lengths and velocities, it can be observed that this is not the case. This result suggests that factors determining flame characteristics are related to the fuel layer burning zone rather than the flame zone above the fuel. A plausible interpretation based on the different models of momentum conservation expressed by Equations (2) and (13) is now offered. For headfires, the momentum change per unit distance along the flame axis involves a number of variables. The drag force on the flame, flame tilt angle, flame depth, and burning rate are strong functions of windspeed, but for any given fire they adjust themselves so that the change in momentum with respect to axial distance is roughly constant. However, the momentum change, which affects flame characteristics, may vary greatly from fire to fire in a given fuel type through changes in D and u_o^2 in Equations (7) for A and B. On the other hand, axial momentum for calm-air fires in similar fuels changes primarily in response to changes in burning rate or flame depth from fire to fire. If wind has but a small effect on burning rates and flame depths of backfires, changes in axial momentum per unit length of flame, and hence flame characteristics, for such fires should correspond to those of fires in calm air even though the flames are tilted. The values of A and B in Equations (7) would tend to be more constant from fire to fire than for headfires. As indicated above, such behavior agrees with experiments reported in this paper. It is consistent also with experimental observations that rates of fuel consumption, rates of spread, and flame depths for headfires are strongly affected by wind but only weakly affected in backfires. On this basis, backfire flame lengths and tip velocities should be described by Equations (16), (17), and (18).

Exceptions to this argument are backfire flame tilt angles and flame heights whose values differ from values for the calm-air case due to their dependence on windspeed. Because backfires have not been analyzed separately, it is assumed that Equation (9) gives flame angles and that Equation (10) with L given by Equation (16) describes flame height. These assumptions should be tested with experimental data.

EXPERIMENTAL DATA

In tests of the theoretical relationships presented in this paper, Equations (8), (12), (16), (17), and (18) will be compared with experimental data on flame lengths and velocities. No tests of flame heights or angles are made because of incomplete data.

Procedures

Information on fire behavior and flame characteristics was collected from field burns of operational size (roughly 15 to 200 acres burned) conducted during February and March 1975. The fires were burned in southern fuels such as pine litter under plantations, mixtures of litter and grass, and the palmetto-gallberry stands of Georgia and northern Florida. The data are presented in table 1. All fires but two (Leesville, La., and Pierson, Fla.) were burned as backfires, but some data were taken on three of the backfires during periods when the fires had been switched to a headfire mode of spread by variable winds. The reported fire behavior measurements are averages and do not correspond to specific time intervals during which flame measurements were made.

Fire-spread rates were measured by using reference stakes a known distance apart along several lines perpendicular to the expected direction of spread. A team of observers timed the fire front as it passed each stake. Later, the movement of the entire front was mapped, and an average rate of spread determined for the burn.

Vegetation and litter weights were obtained with a double-sampling technique. Fuel information on 100 equidistant ¼-milacre plots within the main plot was recorded by an observer who walked along transect lines and estimated weights by species, condition (living or dead), and size

Table 1.—Fire behavior measurements for 1975 field burns in southern fuels[1]

Fire location	Fuel type	Mode of spread	No. film segments	Fuel consumption (W_a)	Rate of spread (R)	Flame length (L)	Flame tip velocity (u_L)	Byram's fire intensity[2] (I)
				lb/ft²	*ft/sec*	*ft*	*ft/sec*	*Btu/ft-sec*
Waycross, Ga.	pal-gal	B[3]	16	0.36	0.022	2.3 ± 0.2	11.4 ± 0.8	48
Waycross, Ga.	pal-gal	B	5	.28	.042	3.0 ± .4	9.3 ± 1.3	71
Macon, Ga.	pine-hdwd	B	13	.10	.050	.90 ± .14	7.3 ± .9	29
Macon, Ga.	pine-hdwd	H[4]	5	.10	—	1.1 ± .3	11.5 ± 1.7	—
Barberville, Fla.	pal-gal	B	10	.30	.022	2.5 ± .4	11.7 ± .8	40
Pierson, Fla.	pal-gal	H	3	.11	.170	1.5 ± .2	12.4 ± 1.1	112
Macon, Ga.	lit-grass	B	10	.13	.018	.73 ± .15	7.0 ± .6	14
Leesville, La.	lit-grass	H	10	.09	.072	.85 ± .10	8.2 ± .8	38
Kirbyville, Tex.	pine-hdwd	B	5	.10	.012	.46 ± .05	3.5 ± .5	7
Kirbyville, Tex.	pine-hdwd	B	5	.06	.021	.51 ± .13	7.2 ± 2.4	8
Kirbyville, Tex.	pine-hdwd	H	2	.06	—	2.1 ± .7	24.0 ± 11.8	—
Macon, Ga.	pine-hdwd	B	8	.12	.044	.83 ± .12	7.0 ± 1.3	32
Macon, Ga.	pine-hdwd	H	2	.12	—	3.7 ± .26	34.7 ± 9.3	—
Macon, Ga.	pine-hdwd	B	10	.08	.012	.51 ± .13	5.9 ± .8	6
New Bern, N.C.	lit-shrubs	B	12	.10	.051	1.6 ± .3	9.1 ± 1.1	31

[1] All measurements made by Fuels and Fire Behavior Team of the Smoke Management Research and Development Program, Southern Forest Fire Laboratory, Macon, Georgia, under leadership of W. A. Hough.

[2] Heat yield is 6,000 Btu/lb for computation of I.

[3] B = backfire mode.

[4] H = headfire mode.

class. Approximately 10 percent of these plots were also physically sampled by species, condition, and size class. The measurements were used to devise a method for correcting the visual estimates. This sampling procedure was followed before and after the burn to determine fuel consumption.

Flame characteristics were recorded with a movie camera mounted on a tripod and operated at 64 frames per second. Filming was parallel to the fireline. Short segments of film (usually about 5 to 10 seconds each) were used to make exposures of the flame as the fire burned into the camera's field of view. Flame lengths, velocities, and angles were determined later from the flame images displayed on a screen. A standard length was included in each frame to provide a reference for distance measurements. Velocities were estimated by selecting a small parcel of flame and noting its change in location from frame to frame on the screen. Frame speed was then used to obtain velocity. These measurements were usually made near the image of the flame tip. Flame tilt angles (and hence the corresponding heights) were obtained also, but are not discussed further in this paper because windspeeds are not known with sufficient accuracy to allow meaningful tests of Equations (9) and (10).

RESULTS AND DISCUSSION

The flame characteristics data of table 1 are averages from a number of segments filmed during a given fire, and are presented with corresponding standard errors of the mean. Suitable film segments for fires in the headfire mode of spread were usually fewer than for fires in the backfire mode of spread. Though flame characteristics continually fluctuated due to variations in wind direction, turbulence, and differences in fuel consumption, it was expected that meaningful relationships could be obtained without use of a statistical design and analysis because of guidelines from the theoretical results. Table 1 also gives fire intensities, which were computed from averaged measurements of fuel consumption and spread rate when available.

The data of table 1 are presented in figures 2 and 3. Figure 2 shows backfire flame lengths and velocities as functions of fire intensity. For headfires, such plots are omitted because of inadequate rate of spread data. The slopes of the lines in figure 2 have been plotted according to predictions of Equations (16) and (17). Intercepts have been determined visually. The experimental values fall close to these lines with a reasonable amount of scatter. In figure 3, headfire and back-

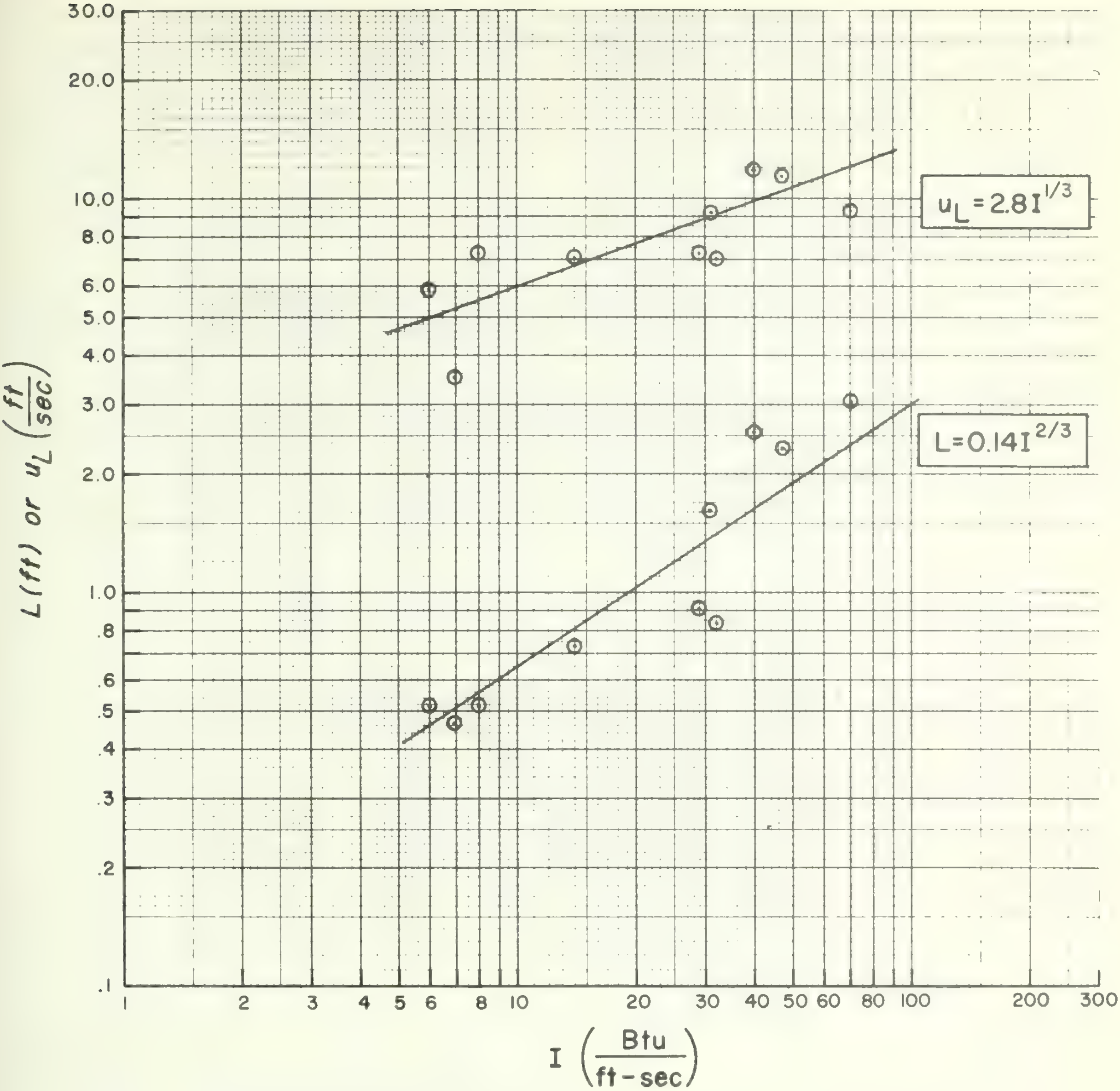

Figure 2.—Flame length and flame tip velocity data for backfires in southern fuels. The equations shown are visual fits of the data constructed with theoretical slopes from Equations (16) and (17).

fire flame velocities are related to flame lengths. The slopes of the lines have been constructed in accordance with Equations (12) and (18). As before, intercepts have been located visually. Although some scatter is present, the agreement between theory and experiment is good.

Another test of Equations (12), (16), (17), and (18) is to assign "reasonable" values to the multiplying factors and predict the constants obtained empirically in figures 2 and 3. The quantities E and r in these equations are not as well known as the other factors, and are assigned values based on estimates of previous investigators. For flames above line fires in cribs, Thomas (1963) has used an entrainment constant given, in the notation of this paper, by

$$E' = 0.16\left(\frac{\rho_o}{\rho_a}\right)^{1/2}$$

for a one-sided flame. To account for both sides of the flame, E′ must be doubled. It is believed that a realistic value of ρ_o/ρ_a for fires in southern fuels is 0.25. Thus, we obtain

$$E = 2E' = 0.16$$

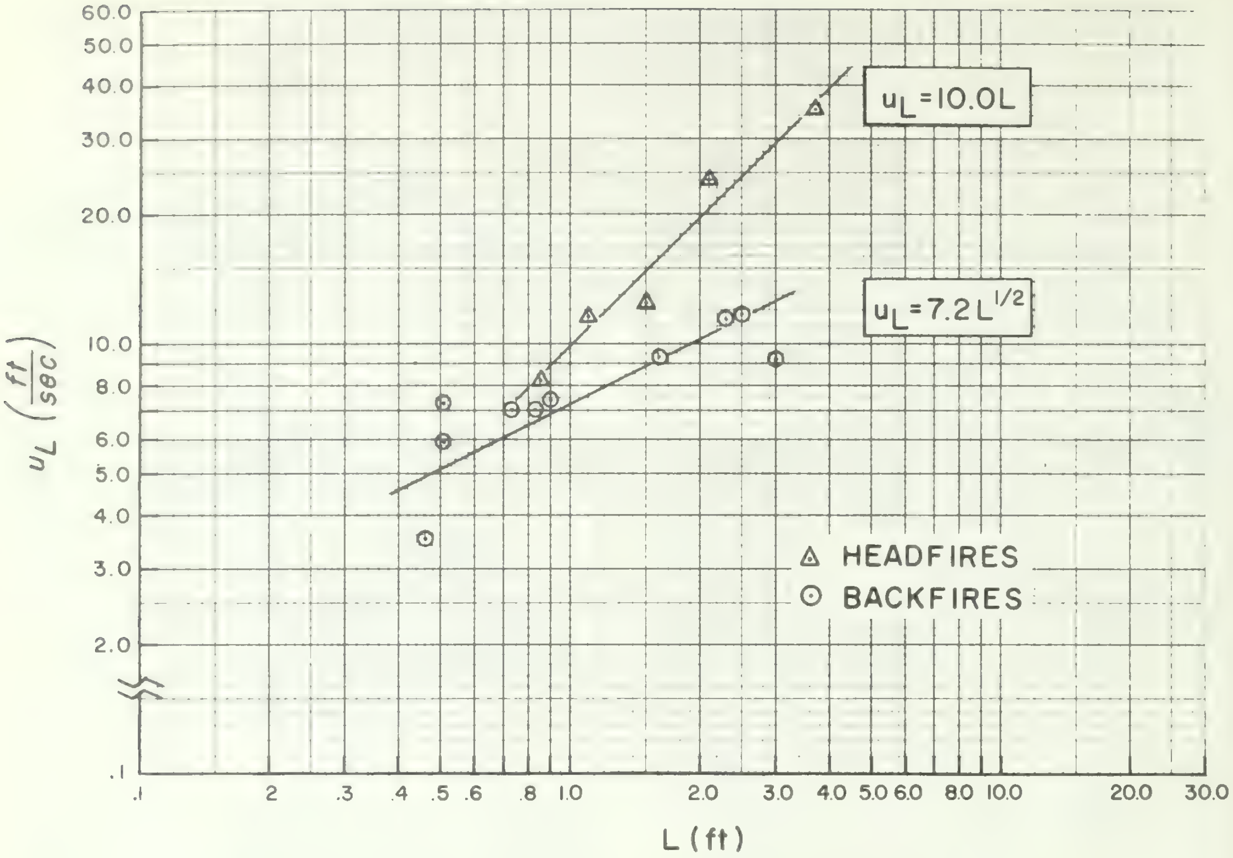

Figure 3.—Flame length–flame tip velocity relationships for headfires and backfires in southern fuels. The equations shown are visual fits of data constructed with theoretical slopes from Equations (12) and (18).

with E assumed independent of all other fire and weather variables. A constant value of r is used, although r probably varies from fire to fire. The stoichiometric air-fuel requirement on a mass basis depends on fuel composition, and is approximately 6 lb/lb. It is also unclear how much air in excess of the stoichiometric amount is involved in free-burning fires. Thomas (1965) has measured the horizontal air flow toward a burning crib 3 feet in diameter, and reports an r value of 60. He points out, however, that a large fraction of this air does not enter the flame zone. Steward (1964) compared experimental and theoretical flame heights for burning liquid fuels and found good agreement when 200 percent excess air was assumed for r. Van Wagner (1974) has used 100 percent excess air in his studies on crown fires. For purposes of this paper, 100 percent excess air is assumed, resulting in r = 12 lb/lb. The remaining quantities are g, ρ_o/ρ_a, ρ_a, H, and I_R; they are assigned the values 32 ft/sec^2, 0.25, 0.075 lb/ft^3, 6,000 Btu/lb, and 30 Btu/ft^2-sec, respectively.

Substitution of the proper numbers into Equations (16) and (17) for backfires results in

$$L = 0.21\ I^{2/3} \tag{19}$$

$$u_L = 3.5\ I^{1/3} \tag{20}$$

which will overestimate L and u_L according to the relationships given in figure 2. The agreement is well within a factor of 2, however, and seems reasonable in view of the many approximations made in deriving Equations (19) and (20).

Flame velocity–flame length relationships can be tested by substitution of the above numbers into Equations (12) and (18). The results are given by

$$u_L = 8.1\ L \tag{21}$$

for headfires and by

$$u_L = 7.7\ L^{1/2} \tag{22}$$

for backfires. Agreement is within 20 percent of the experimental results in figure 3.

Also of interest is a comparison of Equation (8) for headfire flame lengths with the empirical flame length equation given by Byram (1959). This equation is $L = 0.45\, I^{0.46}$. If it is assumed that 30 Btu/ft²-sec adequately represents the I_R values associated with Byram's experimental fires, substitution of the appropriate numbers into Equation (8) gives

$$L = 0.27\, I^{1/2}. \tag{23}$$

Within the range of fire intensity of interest for prescribed fires in the South ($I < 200$ Btu/ft-sec), Equation (23) yields flame lengths that are smaller than those predicted by Byram by a factor of 30 percent or less.

Sneeuwjagt and Frandsen (1977) reported experimental measurements of flame length, fuel loading, rate of spread, and flame depth for headfires in grass fuels. The fire intensity and reaction intensity based on a heat yield of 6,000 Btu/lb were computed from these observations. A plot was constructed of L versus I (with the exception of fires CF-3C and CWF-2) and is presented in figure 4 with groups of data identified according to the associated values of I_R. These values ranged from about 5 to 180 Btu/ft²-sec, based on the reported ocular observations of flame depth. The relationship in figure 4, with slope constructed in accordance with Equation (23), is in good agreement with the data and thus supports the notion that headfire flame lengths are proportional to the square root of fire intensity. The four data points for $I < 4$ Btu/ft-sec seem unusually far removed from the remaining data. The reasons for this result are unclear. One explanation could be given in terms of errors in visual estimates, which probably increased as I_R decreased. Another possibility is that flow of gases in the flame tends to become nonturbulent for small values of I_R, causing a change in the relationship between L and I. In any case, the dependence of L on I_R at constant I is not in accordance with predictions of Equation (8). Further studies of the effect of I_R are needed.

SUMMARY

Equations describing forest fire flames in terms of turbulent jets have been solved and relationships derived for flame lengths, angles,

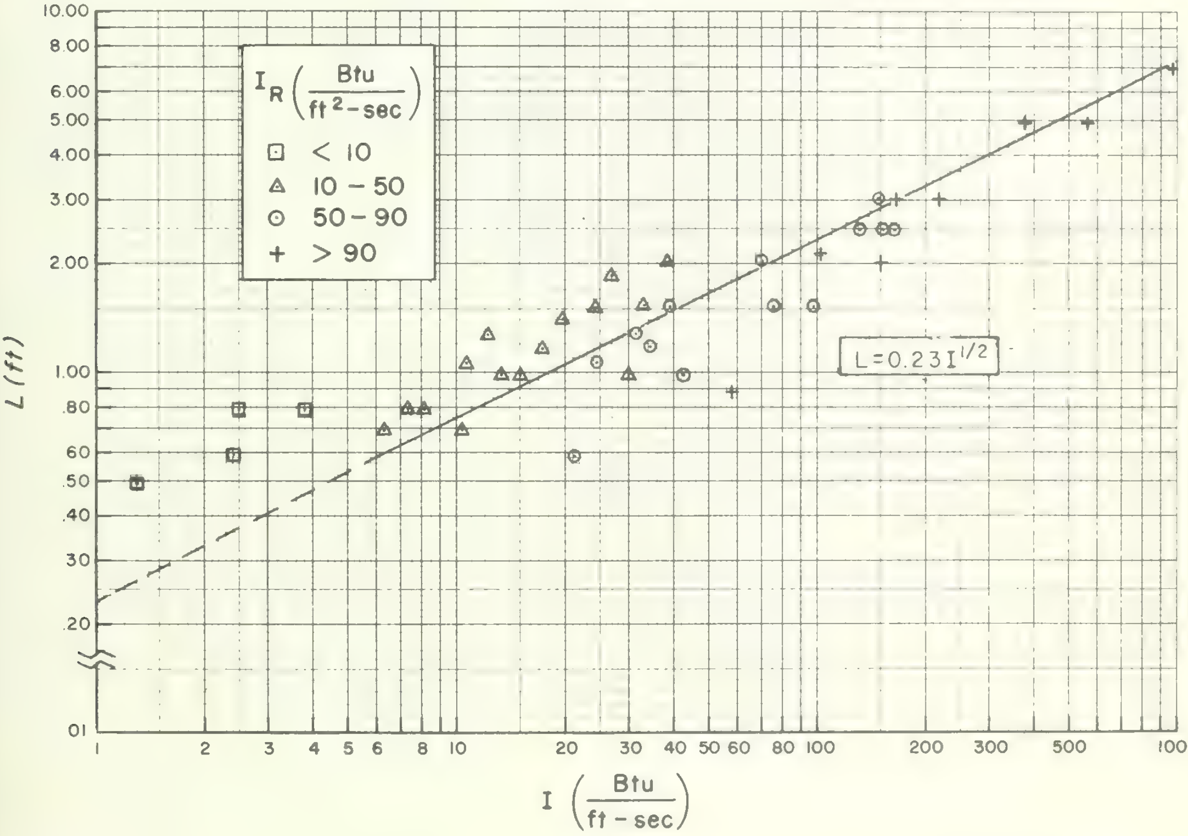

Figure 4.—Flame length data of Sneeuwjagt and Frandsen (1977) for headfires in grass fuels grouped according to values of I_R. The equation shown is a visual fit of the data constructed with the theoretical slope from Equation (23).

heights, and tip velocities for flames in wind and in calm air. Flame length and velocity data from low-intensity fires (less than 120 Btu/ft-sec) in southern fuels were used to test the theoretical relationships. It was found that backfire data were described by the equations for calm-air conditions.

Contingent on the assumption that I_R is nearly constant from fire to fire, the most significant results of this paper can be summarized as follows:

(1) Theoretical considerations and experimental work in the literature suggest that headfire flame lengths vary as the square root of Byram's fire intensity.

(2) Thomas' relationship expressing flame length as proportional to the ⅔ power of fire intensity apparently applies to backfires and fires in calm air.

(3) Relationships between flame lengths and flame velocities differ for headfires and backfires in southern fuels.

As is true of most mathematical models, this particular attempt to describe flame characteristics involves many approximations made in the model itself, in the solutions of the equations, and in the data used to test some of the relationships. Nevertheless, the theory agrees with experiment—both in form and in prediction of constant multipliers (well within a factor of 2). More work is needed with fires burned over a greater range of fire intensity and in a variety of fuel and weather conditions to further verify these results.

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APPENDIX I

DERIVATION OF HEADFIRE FLAME CHARACTERISTICS

Equations (4) to (7) of the text are used to derive headfire flame lengths, angles, heights, and tip velocities. We begin by defining the variables a and b as

$$a = u'y'$$

$$b = u'^2y'$$

so that $u' = b/a$ and $y' = a^2/b$. Thus, Equations (5) and (6) become

$$(da/dx') = Au' = A(b/a) \qquad \text{(I-1)}$$

$$(db/dx') = B. \qquad \text{(I-2)}$$

Integration of Equation (I-2) with the condition that $b = \cos\Theta = y'$ when $x' = 0$ gives

$$b = Bx' + \cos\Theta. \qquad \text{(I-3)}$$

Integration of Equation (I-1) with Equation (I-3) substituted for b and the condition that $a = \cos\Theta$ when $x' = 0$ results in

$$a = [ABx'^2 + 2A\cos\Theta\, x' + \cos^2\Theta]^{1/2}. \qquad \text{(I-4)}$$

Flame Length

Flame length, L, is defined as the distance along x′ at which an amount of air, r pounds per pound of unburned fuel flowing through the surface, has been entrained into the flame zone. At the flame tip,

$$(2\rho_o uy/\rho_o u_o D) = u'y' = a = r + 1. \qquad \text{(I-5)}$$

Thus, at $x' = L/D$, $(r + 1)$ pounds of combustion products flow through the flame tip for every pound of fuel-products mixture flowing through the burning surface layer of depth D. It can be shown that, except when $L << D$ which is not of interest here, the quantity ABx'^2 in Equation (I-4) greatly exceeds the quantity $[2A\cos\Theta\, x' + \cos^2\Theta]$. Therefore, Equations (I-4), (I-5), and (7) from the text can be combined into the approximate form

$$L = \left[\frac{(r + 1)^2\rho_o^2u_o^2D^2}{E\rho_a gD(\rho_a - \rho_o)}\right]^{1/2}. \qquad \text{(I-6)}$$

The quantity $\rho_o u_o D$ is evaluated through the assumption that air is supplied to the combustion zone at a rate equal to r/5 times the mass burning rate per unit length of fireline and is involved in combustion below the fuel surface. This figure is an arbitrary one, and probably varies with fire size and intensity. However, the occurrence of flaming combustion below the surface clearly indicates that some oxygen is flowing into that region of the combustion zone. Thus,

$$\rho_o u_o D = \left(\frac{r + 5}{5}\right)RW_a = \left(\frac{r + 5}{5}\right)\frac{I}{H} \qquad \text{(I-7)}$$

where R is the rate of fire spread, W_a is the weight of fuel consumed per unit area,[3] H is heat yield, and I is fire intensity as defined by Byram (1959). Substitution of Equation (I-7) into Equation (I-6) and use of the relation between fire intensity and reaction intensity

$$I_R = I/D \qquad \text{(I-8)}$$

results in the expression

$$L = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{I_R}{Eg(1 - \rho_o/\rho_a)}\right]^{1/2} I^{1/2} \qquad \text{(I-9)}$$

which reduces to a form nearly identical to Byram's empirical result ($L = 0.45\ I^{0.46}$) for a series of fires in which multipliers of $I^{1/2}$ do not change appreciably.

Flame Tilt Angle

Flame tilt angle, Θ, defined as the tilt of the flame axis from the vertical direction, is determined from Equation (4) of the text and Equation (I-8) as

$$\tan\Theta = \frac{C_F U^2}{2gD(1 - \rho_o/\rho_a)}$$

$$= \frac{C_F U^2 I_R}{2gI(1 - \rho_o/\rho_a)} \qquad \text{(I-10)}$$

---

[3] A distinction is not made between total fuel consumed and fuel available for flaming combustion, which strictly applies here.

which implies that tan Θ is proportional to U^2/I for headfires with constant I_R, C_F, and ρ_o.

Flame Height

Flame height, h, is the perpendicular distance from the flame tip to the ground. Equation (I-10) can be used to write h as

$$h = L\cos\Theta = L\left\{1 + \left[\frac{C_F U^2 I_R}{2gI(1 - \rho_o/\rho_a)}\right]^2\right\}^{1/2} \tag{I-11}$$

Substitution of Equation (I-9) for L yields

$$h = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{I_R I}{Eg(1 - \rho_o/\rho_a)}\right]^{1/2} \times \left\{1 + \left[\frac{C_F U^2 I_R}{2gI(1 - \rho_o/\rho_a)}\right]^2\right\}^{-1/2} \tag{I-12}$$

If winds are strong and $(C_F U^2/2) >> gD(1 - \rho_o/\rho_a)$, h can be written approximately as

$$h = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{4g(1 - \rho_o/\rho_a)}{C_F^2 U^4 I_R E}\right]^{1/2} I^{3/2} \tag{I-13}$$

None of the above equations for h is valid at very small values of U and Θ because Equation (I-9) does not apply when U and Θ approach zero.

Flame Tip Velocity

Flame tip velocity is the rate of movement of flame gases in the axial direction near the tip of the visible flame. An equation for u′ can be written, from definitions of a and b and Equations (I-3) and (I-4), as

$$u' = \frac{u}{u_o} = \frac{b}{a} = \frac{Bx' + \cos\Theta}{[ABx'^2 + 2A\cos\Theta x' + \cos^2\Theta]^{1/2}}.$$

We evaluate u′ by retaining only the first terms in the numerator and square of the denominator. This simplification would be most valid for strong winds when cos Θ is small, or when $x' >> 1$; that is, for tall, narrow flames. Thus, as x′ approaches L/D, u approaches the flame tip velocity, u_L, and

$$u_L = u_o\left(\frac{B}{A}\right)^{1/2} = \left[\frac{gD}{E}(1 - \rho_o/\rho_a)\right]^{1/2}$$

from Equations (7) of the text. Using Equation (I-8), we obtain

$$u_L = \left[\frac{g}{EI_R}(1 - \rho_o/\rho_a)\right]^{1/2} I^{1/2} \tag{I-14}$$

which implies that u_L is proportional to $I^{1/2}$ if multipliers of $I^{1/2}$ are constant.

APPENDIX II

DERIVATION OF CALM-AIR FLAME CHARACTERISTICS

Equations (14) and (15) of the text are used to derive flame lengths and tip velocities. The variables a and b are defined as in Appendix I. Thus, Equations (14) and (15) can be written as

$$(da/dx') = A(b/a) \qquad \text{(II-1)}$$

$$(db/dx') = B(a^2/b) \; . \qquad \text{(II-2)}$$

Division of these two equations gives

$$(db/da) = (B/A)a^3/b^2$$

and integration subject to the condition that b = 1 when a = 1 results in

$$b = [(3/4)(B/A)(a^4 - 1) + 1]^{1/3}$$

which can be approximated by

$$b = [(3/4)(B/A)a]^{1/3}a \qquad \text{(II-3)}$$

because (B/A) >> 1 and we consider applications in which a > 1. Substitution of Equation (II-3) into Equation (II-1) and integration with the condition that a = 1 when x′ = 0 yields

$$a^{2/3} = \tfrac{2}{3}\,[(3/4)(A^2B)]^{1/3}x' + 1. \qquad \text{(II-4)}$$

Flame Length

Substitution of Equation (I-5) and Equations (7) of the text into Equation (II-4) when x′ = L/D gives

$$L = \left[\frac{9[(r+1)^{2/3} - 1]^3\rho_o^2u_o^2D^2}{2\rho_a^2E^2g(\rho_a/\rho_o - 1)}\right]^{1/3} . \qquad \text{(II-5)}$$

Equation (I-7) used in this equation gives

$$L = \left[\frac{9(r^2 + 10r + 25)\;[(r+1)^{2/3} - 1]^3}{50H^2E^2\rho_a^2g(\rho_a/\rho_o - 1)}\right]^{1/3} I^{2/3} \qquad \text{(II-6)}$$

which agrees with the dimensional considerations of Thomas (1963) for strip sources of infinite length in calm air when the factors multiplying $I^{2/3}$ are constant.

Flame Tip Velocity

The gas velocity at the flame tip is obtained from Equation (II-3) which can be written as

$$u' = \frac{u}{u_o} = \frac{b}{a} = \left[\frac{3gD(1 - \rho_o/\rho_a)a}{4Eu_o^2}\right]^{1/3}$$

using Equations (7) of the text. Because $u = u_L$ and a = r + 1 at the flame tip, Equation (I-7) may be used to express u_L as

$$u_L = \left[\frac{3(r^2 + 6r + 5)g(1 - \rho_o/\rho_a)}{20EH\rho_o}\right]^{1/3} I^{1/3} \qquad \text{(II-7)}$$

which also conforms to a well-known scaling law for turbulent flow above line sources (Taylor 1961) when r, ρ_o, and E are constant.

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Nelson, Ralph M., Jr.
1980. Flame characteristics for fires in southern fuels. USDA For. Serv., Res. Pap. SE-205, 14 p. Southeast For. Exp. Stn., Asheville, N.C.

A flame model and analytical method are used to derive forest fire flame characteristics. Approximate solutions are used to express flame lengths, angles, heights, and tip velocities of headfires and calm-air fires in terms of fire intensity. Equations are compared with data from low-intensity controlled burns in southern fuels and with data from the literature.

KEYWORDS: Flame length, flame velocity, flame angle, fire intensity, buoyant flames

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The Forest Service, U.S. Department of Agriculture, is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives—as directed by Congress—to provide increasingly greater service to a growing Nation.

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Research Paper

SE-206

Moisture Conditions of a Joist Floor Over an Insulated and Sealed Crawl Space

by John E. Duff

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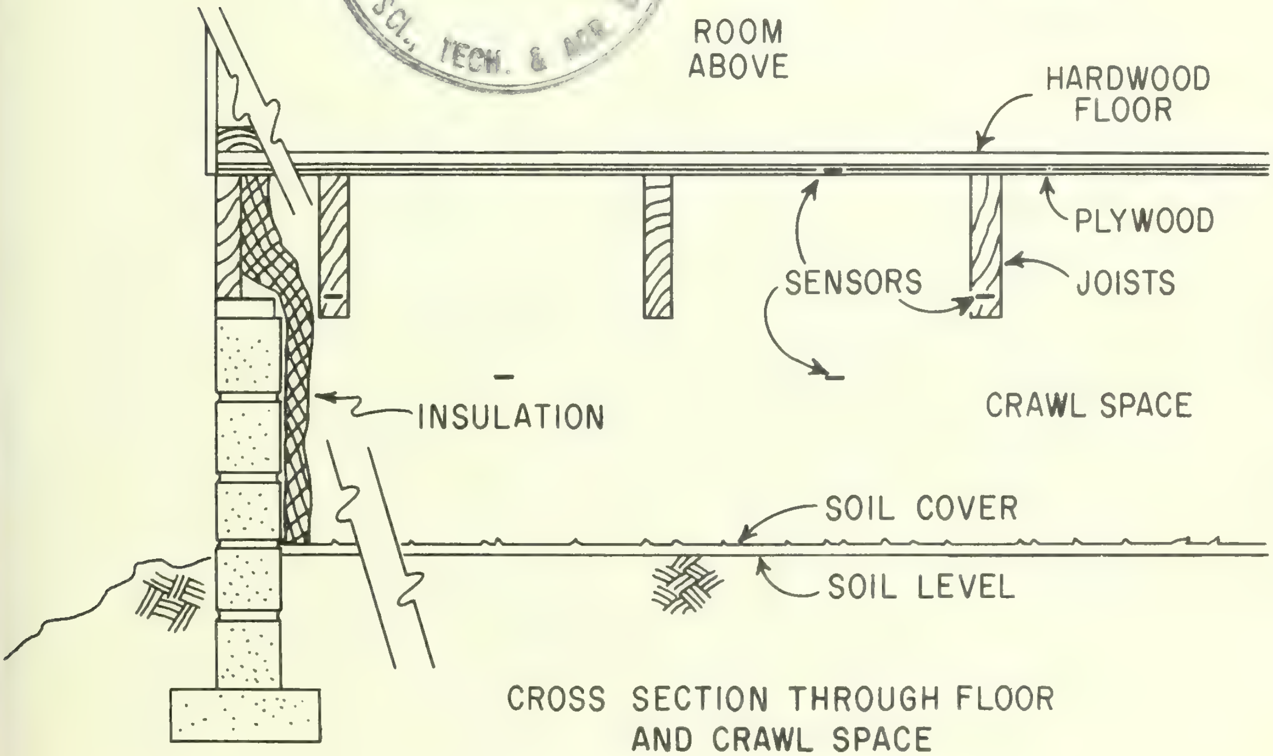

CROSS SECTION THROUGH FLOOR AND CRAWL SPACE

June 1980

Southeastern Forest Experiment Station

Asheville,North Carolina

Moisture Conditions of a Joist Floor Over an Insulated and Sealed Crawl Space

by

John E. Duff, Research Scientist
Forestry Sciences Laboratory
Athens, Georgia

ABSTRACT.—A 30-month study of the moisture in a joist floor over an insulated crawl space with sealed vents showed a summertime maximum moisture content in the floor of almost 17 percent when a full plastic soil cover was used. When the soil cover was opened to expose 10 percent of the soil area, the moisture in the floor reached a summertime maximum of 19 percent. Minimum moisture content of less than 10 percent was reached in winter. These results show that moisture condensation will not be a problem in floors over well-drained, insulated crawl spaces with sealed vents when a 90 to 100 percent soil cover is used.

Keywords: Relative humidity, floor sheathing, soil cover, floor plenum.

Homeowners can save heating and cooling energy by installing floor and ductwork insulation in residences built with crawl-space floors. However, insulating these areas of the house is costly in both labor and materials.

Fortunately, an alternative method is available that is less costly, eliminates the need to insulate the heating ductwork and water pipes, and provides the added benefit of warm floors during winter. This technique involves insulating the exterior foundation walls and installing a soil cover to control relative humidity in the crawl space. This insulation method is permitted under the provisions of HUD MPS 4900.1 for one- and two-family dwellings,[1] provided that the crawl-space temperature can be maintained at 50° F or higher—a requirement that can be met in almost all sections of the country.

To ensure a 50° F minimum in the crawl space, all foundation vents must be closed during the winter heating season. Since this method of insulation uses a soil cover to limit crawl-space relative humidity, standard venting can be reduced 90 percent or 1/3000th of the floor area. Two vents are still necessary to obtain cross ventilation when needed (*see* footnote 1).

Although insulating the foundation walls would save energy, some builders and homeowners may be concerned about moisture hazards which may be created by reducing the crawl-space venting requirements so drastically. Will the floor moisture conditions increase to dangerous levels if the homeowner forgets to open his foundation vents during the summer months? Could hazardous floor moisture be created if the soil under the floor is not fully covered by the soil cover?

This Paper reports on the results of a 30-month study of crawl-space floor moisture in a test house. The amount of floor moisture resulting from properly and improperly installed soil covers is discussed, along with the effects of keeping the foundation vents closed all year.

METHODS

TEST HOUSE AND FLOOR SYSTEM

Researchers conducted this study in a test house located near Athens, Georgia. It was located in an open, unshaded, well-drained site on a gently sloping hillside (fig. 1). The 24- by 24-foot house was constructed with an 8- by 24-foot joist floor across one-third of the house in the rear. A concrete-block foundation wall separated the 8- by 24-foot crawl space from the rest of the area

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[1] U.S. Department of Housing and Urban Development. 1973. Minimum property standards for one- and two-family dwellings, 4900.1. U.S. Dep. Housing and Urban Dev., Washington, D.C.

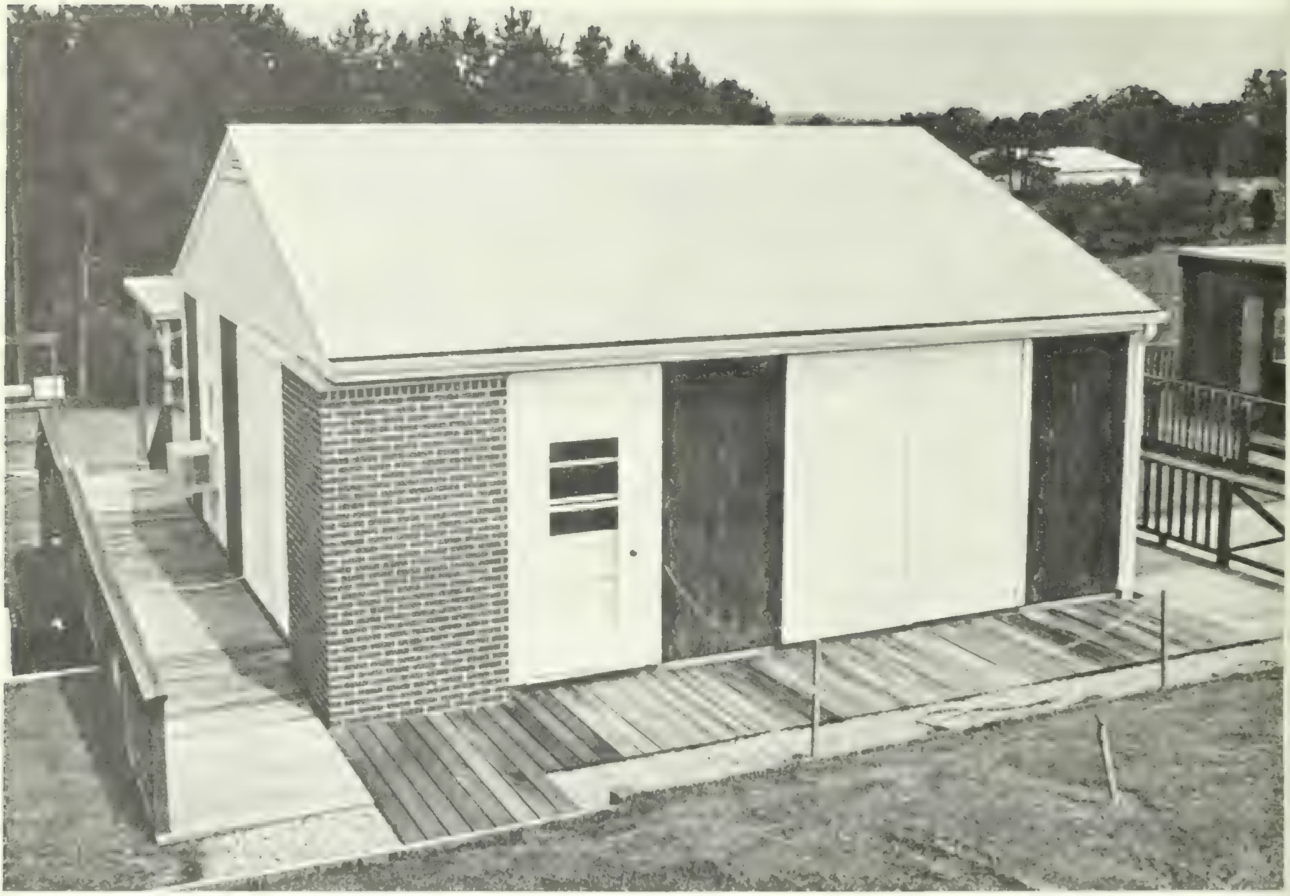


Figure 1.—The environmental test house near Athens, Georgia, with the crawl-space floor constructed across the rear third of the structure.

under the floor. The height of the crawl space varied from 29 to 33 inches from the soil to the bottom of the floor joists. Above the floor, an interior partition divided the 8- by 24-foot room from the remainder of the space above the floor.

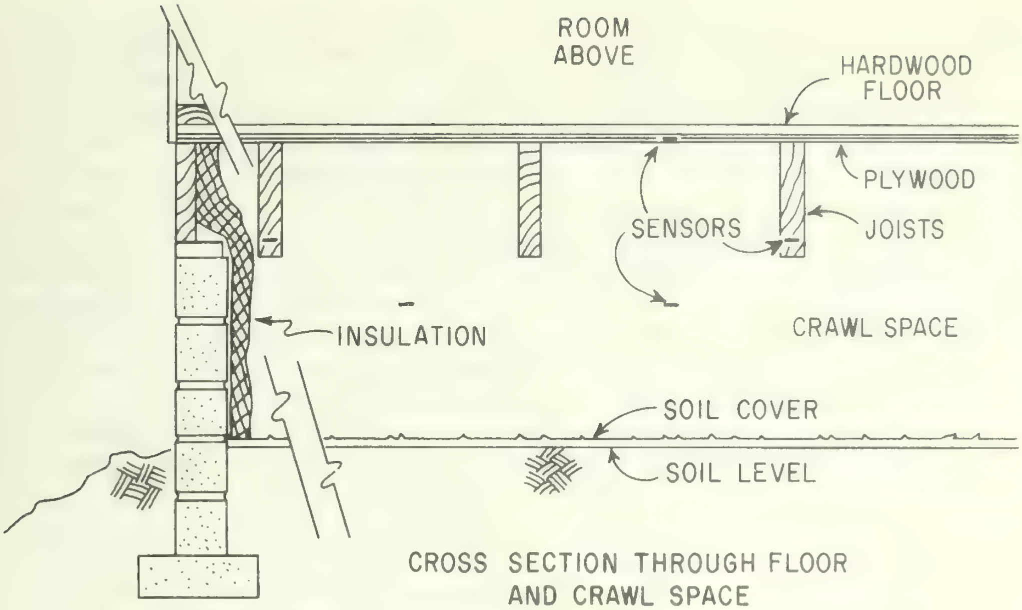
The test floor was constructed with 2- by 8-inch joists of southern pine, 16 inches on center, running in the 8-foot direction. The joists were overlaid with 5/8-inch sheathing-grade southern pine plywood, over which technicians nailed ¾-inch oak strip flooring, sanded and sealed with two coats of commercial-grade floor varnish. No cross bridging was used between joists.

The concrete-block foundation wall was covered with 3½-inch-thick batts of 24-inch wide fiberglass insulation. The vapor barrier on the batt insulation was positioned toward the inside of the crawl space. After each batt was cut to length, the upper end of the batt was stapled to the band joist. The batt was draped vertically with the lower batt end touching the soil cover. After all the batts were installed, the flange along the length of the batts was stapled together and taped.

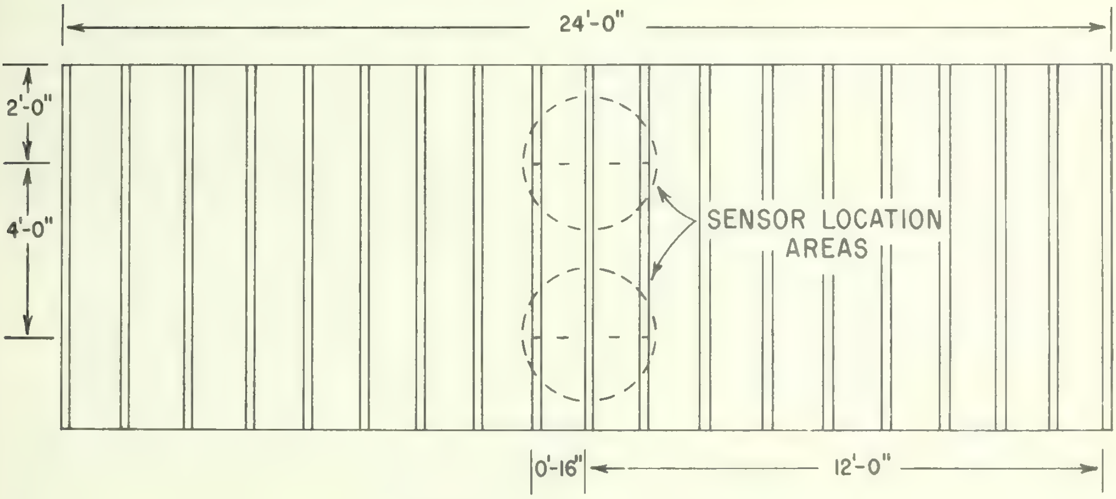
Special care was exercised to position the 0.006-inch-thick polyethylene soil cover 12 inches up the foundation walls behind the batt insulation (fig. 2). All vents in the crawl-space foundation walls were sealed with ½-inch plywood and caulked. The access door to the crawl space was insulated and weather stripped.

MOISTURE MEASUREMENTS

A total of four sheathing and four joist moisture sensors were installed in the test floor. In addition, two air moisture sensors were hung 4 inches below the bottom edges of the joists in approximately the center of the test floor. The moisture sensors in the crawl-space air measured the equilibrium moisture content (EMC) of the air which indicates the moisture content wood will reach when exposed to crawl-space air. Sensor wiring was routed to the room above the test floor where it was connected to the moisture measurement equipment.



CROSS SECTION THROUGH FLOOR AND CRAWL SPACE



BOTTOM VIEW OF FLOOR

Figure 2.—Location of moisture sensors in the test floor.

Figure 2 shows the positions of the sensors[2] sed to measure the moisture of the floor. The oor and wall cross section indicates the location f the joist and sheathing sensors. The joist ensors were installed and sealed inside the joists inches from the lower edge. The plywood ensors were positioned midway between the joists and sealed in the center veneer ply of the sheathing. Moisture in the oak flooring was not measured. In the bottom view of the floor and sensors, note that the area of measurement was confined to the middle third of the joist floor to minimize any edge effects.

EXPERIMENTAL PROCEDURE

The interior temperature of the room above the test floor was kept at 75° ± 5° F throughout the 30-month study by a window-mounted heat pump. During the winter a floor humidifier controlled the relative humidity at 30 ± 5 percent. During the summer cooling season, the relative humidity was not controlled but the dehumidifying action of the heat pump kept the room humidity below 70 percent.

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[2] Duff, John E. 1966. A probe for accurate determination f moisture temperature of wood products in use. U.S. Dep. gric., For. Serv., Res. Note FPL-0142, 10 p. U.S. Dep. gric., For. Serv., For. Prod. Lab., Madison, Wis.

During the first 22 months of the study the crawl-space soil was completely covered by a soil cover. For the last 8 months, the soil cover was opened to expose 10 percent of the soil area directly under the center of the test floor.

The test room was unoccupied during the study except for monthly visits to take measurements. All measurements were made at midday. Temperature-adjusted moisture data for the plywood floor sheathing, wood joists, and crawl-space air were averaged separately and plotted for analysis.

RESULTS

Figure 3 shows the average EMC of the crawl space, joists, and plywood sheathing during the 30-month study. Floor moisture was rather high at the start of the study, but the moisture-controlling effects of the soil cover are shown rather dramatically by the rapid decline in the floor moisture content during the first summer of the study.

During the fall of 1976, moisture in the floor and crawl-space air continued to decrease. By January 1977, the floor sheathing and joists had reached a low of 9 to 10 percent moisture—a drop which is quite typical in the fall for crawl-space floors with or without soil covers.[3]

The moisture would have been even lower if heat ducts had been placed in the crawl space. Any heating of the air below the floor, either by heat conducted through the floor or by heat gained from uninsulated ducts, lowers the relative humidity in the crawl space. Note that the joists and the sheathing dried at about the same rate.

As the weather in Georgia began to warm in February 1977, the moisture in the crawl-space air began to increase, followed by moisture increases in the sheathing and joists (fig. 3). By June, moisture in the floor joists had reached almost 14 percent, and by September it had reached 16 percent in the sheathing. In September, moisture in the wood joists peaked about 1 percent below moisture in the sheathing. The higher sheathing moisture content was probably caused by a slight

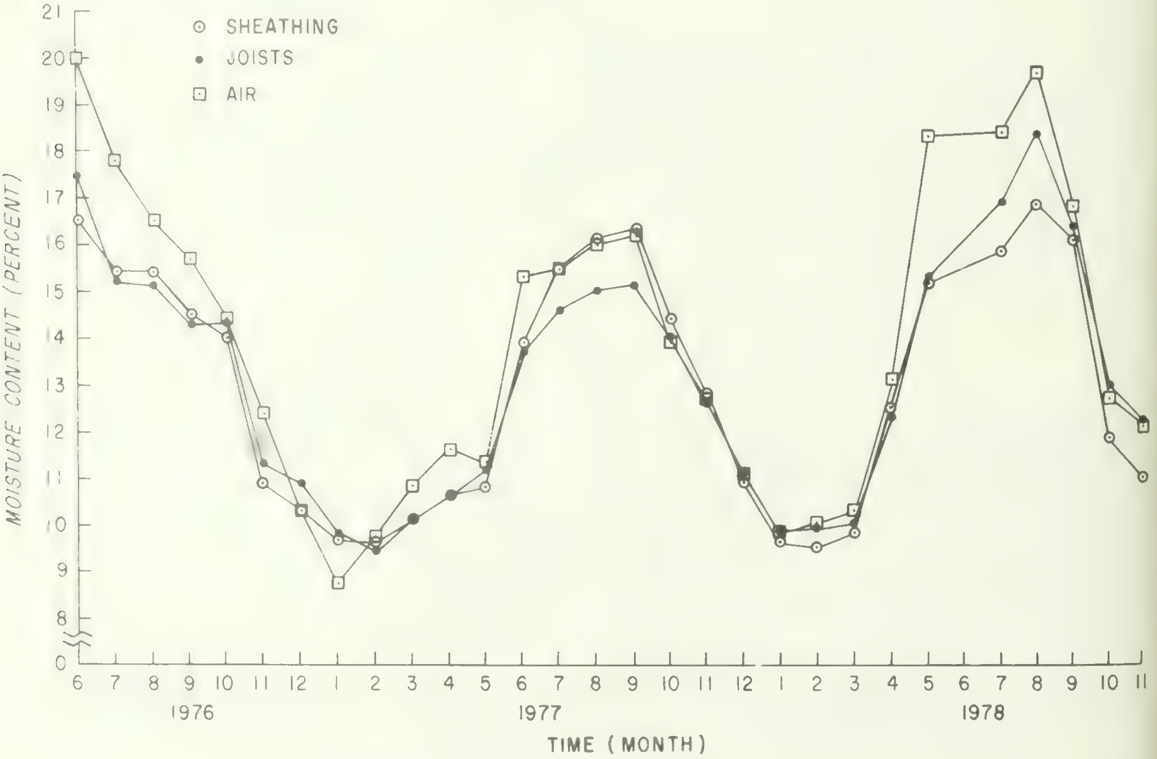

Figure 3.—Average moisture in the sealed, insulated crawl-space air (EMC), joists, and sheathing during the 30-month study.

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[3] Duff, John E. 1978. Moisture content of a joist floor over a crawl space. U.S. Dep. Agric., For. Serv., Res. Pap. SE-189, 12 p. U.S. Dep. Agric., For. Serv., Southeast. For. Exp. Stn., Asheville, N.C.

cooling of the sheathing by the air-conditioned air in the room above. Any cooling of the plywood would increase its moisture since the relative humidity would be slightly higher next to the plywood surfaces.

Moisture data from the summer of 1977 indicate that, if a homeowner forgets to open the crawl-space vents, his floor would become more moist but not moist enough to allow mold and decay fungus to develop. Floor moisture would be reduced if the homeowner opened his vents during warm weather. In comparison, floors over vented crawl spaces without soil covers often reach 20 percent moisture content during the summer months in the South (*see* footnote 3). This level of moisture could support mold fungus.

By late September 1977, the cooler weather started drying the floor and crawl-space air. During the cold months of January and February of 1978, the floor dried to a low of 9 to 10 percent moisture.

Since the soil cover keeps much of the soil moisture from moving into the crawl space, a poorly insulated cover could cause higher floor moisture in the summer if the crawl-space vents were left closed. The effects of a poorly installed soil cover became evident in the last 8 months of the study. After the floor had dried during the previous winter, 10 percent of its area was opened in the middle of the soil cover to simulate poor installation.

The plotted data show that the added moisture from the soil caused a rapid increase in crawl-space air moisture. By May it had reached 18 percent. The floor sheathing and joists reached 15 percent moisture content by May, 2 to 3 months earlier than the previous year when they had 100 percent soil cover. By August, moisture in the sheathing had reached about 17 percent, while it had peaked in the joists at about 18 percent. The crawl-space air had reached almost 20 percent EMC. With the approach of cooler fall temperatures, floor moisture declined rapidly.

The moisture content of the joists was higher than it was in the sheathing because the joists were exposed to the crawl-space air on two sides and one edge, while the sheathing was exposed on just the bottom side. If the crawl-space air had maintained high moisture levels for a longer period, moisture content of the sheathing probably would have approached that in the joists.

The peak joist moisture content of 18 percent is not considered hazardous because it occurred for such a short time. Broken or improperly applied soil covers in crawl spaces with drainage problems or leaking plumbing could give different results. For typical well-drained crawl spaces, the data suggest that bare soil areas of 10 percent would not cause hazardous moisture in a joist floor, even though the homeowner may forget to open the crawl-space vents.

The maximum moisture content observed for this insulated crawl space may indicate the amount that would occur in the plen-wood system.[4] It uses an insulated foundation wall, a 100 percent soil cover, and no foundation venting. The plen-wood system uses the under-floor space as a distribution system for heated and cooled air. Normally during heating and cooling, moisture problems would not develop in the joist floor system since the plenum is filled with the heated or cooled air.

What happens to floor moisture when the plen-wood system is closed down for extended periods? Fall and winter shutdowns would not cause any concern, as indicated by the data shown in this report. A summertime shutdown would result in an increase in floor moisture content, but it would not be high enough for mold or decay fungus to develop.

CONCLUSIONS

Moisture will remain below 17 percent in joist floors constructed over well-drained crawl spaces insulated according to HUD recommendations, even when foundation vents are closed all year. Exposing up to 10 percent of bare soil in the insulated crawl space will not raise the floor moisture content above 19 percent, even when the vents are sealed.

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[4] American Plywood Association. 1978. The plen-wood system. Am. Plywood Assoc., Tacoma, Wash. 21 p.

Duff, John E.
1980. Moisture conditions of a joist floor over an insulated and sealed crawl space. USDA For. Serv., Res. Pap. SE-206, 5 p. Southeast. For. Exp. Stn., Asheville, N. C.

Results of a 30-month study show that moisture condensation will not be a problem in floors over well-drained, insulated crawl spaces with sealed vents when 90 to 100 percent of the soil is covered with plastic.

KEYWORDS: Relative humidity, floor sheathing, soil cover, floor plenum.

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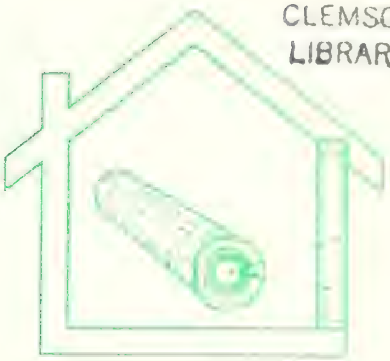

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COM-PLY® REPORT 18

DIMENSIONAL STABILITY AND DURABILITY OF COM-PLY STUDS EXPOSED TO SOAKING, HIGH HUMIDITY, AND WEATHERING

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

COOPERATIVE RESEARCH

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COM-PLY™ is a registered trademark of the American Plywood Association.

July 1980

Southeastern Forest Experiment Station
Asheville, North Carolina

PREFACE

This report is one of a series on the possibilities of producing house framing and structural panels with particleboard cores and veneer facings. These COM-PLY or composite materials were designed to be used interchangeably with conventional lumber and plywood in homes. Research on structural framing was initially limited to COM-PLY studs but has now been extended to include larger members such as floor joists.

In 1973, the home-building industry faced a shortage of lumber and plywood and consequent rising prices. Both industry and government recognized that this situation was not a temporary problem, and that long-range plans for better using the Nation's available forest resources would be necessary.

The Forest Service of the U.S. Department of Agriculture and the U.S. Department of Housing and Urban Development accelerated cooperative research on ways to utilize the whole tree. They concentrated on composite wood products made with particleboard and veneer as a way of using not only more of the tree stem, but also using less desirable trees and a greater variety of tree species than would conventional wood products. The particleboard which comprises a large portion of COM-PLY studs and joists is made from chipped-up wood that comes from forest residues, mill residues, or low-quality timber. Thus, such composites could greatly increase the amount of lumber and plywood available for residential construction, our major use of wood, without eroding the Nation's timber supply.

Research on composite wall and floor framing was performed by the Wood Products Research Unit, Southeastern Forest Experiment Station, Athens, Georgia. The American Plywood Association cooperated in these studies by designing and testing composite panel products that are interchangeable with plywood. Both types of products have been incorporated in demonstration houses.

Included in this series will be reports on structural properties, durability, dimensional stability, strength, and stiffness of composite studs and joists. Other reports will describe the overall project, compare the strength of composite and solid-wood lumber, suggest performance standards for composite lumber, and provide construction details on houses incorporating such lumber. Still others will explore the economic feasibility of manufacturing composite lumber and panels and estimate the amount and quality of veneer available from southern pines. These reports, called the COM-PLY series, will be available from the Southeastern Forest Experiment Station and the U.S. Department of Housing and Urban Development.

ACKNOWLEDGMENT

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DIMENSIONAL STABILITY AND DURABILITY OF COM-PLY STUDS EXPOSED TO SOAKING, HIGH HUMIDITY, AND WEATHERING

by

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Cooperative Research by
U.S. Department of Agriculture, Forest Service
Southeastern Forest Experiment Station

and

U.S. Department of Housing and Urban Development
Division of Energy, Building Technology
and Standards

Abstract.—Exposure of different groups of phenolic-bonded COM-PLY studs to 48 months of weathering, 36 months of high humidity, and 24-hour water soakings resulted in only minor losses in strength and stiffness. Dimensional changes in the COM-PLY studs after these different exposures were small, and no significant distortion occurred. Builders, code officials, and homeowners can be assured that COM-PLY studs will perform as well as or better than conventional stud framing in residential construction.

Keywords: Composite stud exposure, strength loss, stud wetting, distortion.

Successful marketing of COM-PLY wall framing for residential construction depends a great deal on builder and building code acceptance. Builders will use COM-PLY wall studs if they are cost effective and meet performance and use requirements. The studs should be durable, dimensionally stable, and should not distort when exposed to the rigors of construction.

Job-site exposure probably represents the most severe weathering framing studs receive in service. Framing material is often dumped on the job site, stacked and stored on wet ground, drenched with rain, and dried by wind and sun. When covered for weather protection, stud framing is often enveloped by high relative humidity generated by the wet soil under the stack. Even after studs are framed, they are exposed to rain, wind, and sun before the structure is dried in.

The exact effects of weathering on the structural properties of stud framing are not fully understood, hence more definitive information would be valuable for obtaining builder and building code acceptance. For scientists, engineers, or researchers, the information would be helpful in modifying the stud design, the performance standards for studs, or the test methods for evaluating their performance.

This paper reports on three studies conducted to simulate different types of job-site weathering exposure on COM-PLY studs. One laboratory study simulated wetting at the job site, while another simulated exposure of studs to high humidity during or after installation. A third study exposed studs directly to the weather. The COM-PLY studs used in this study were made of two types of resin binders in the particleboard core.

The effects of the three types of exposure on strength, stiffness, dimensional stability, and distortion were evaluated by comparing these properties before and after exposure. Solid-wood spruce studs were used for comparison.

MATERIAL SELECTION FOR TEST STUDS

Three groups of COM-PLY studs and one group of sawn studs were used in the tests as shown in table 1. All COM-PLY studs were fabricated with two plies of B and better grade[1] southern pine veneer 1/6 inch thick by 1½ inches wide and 8 feet long.

For group 1, 90 COM-PLY studs were fabricated in the laboratory from phenolic-bonded particleboard (40 lb/ft³) pressed to a thickness of 1½ inches. Core strips were cut from particleboard panels that measured 2⅞ inches wide and 8 feet long. Pairs of veneer strips were parallel laminated with phenol-resorcinol adhesive. After curing, the laminated veneer strips were glued to the narrow edges of the particleboard cores.

Table 1.—Description of materials used in each group of test studs

Stud group No.	Method of fabrication	Laminating adhesive spread rate		Particleboard binder type	Type exposure test		
		Veneer to veneer	Veneer to particleboard		Water soak	High humidity	Outdoor weathering
		..... *Lb/M ft²*					
1	Laboratory	40	90–100	Phenolic			x
2	Factory[1]	45	90–100	Phenolic	x	x	
3	Laboratory	40	80	Urea			x
4	Sawmill	—	—	—	x	x	x

[1] Vick, Charles B. 1977. Adhesives for COM-PLY studs. U.S. Dep. Agric., For. Serv., Res. Pap. SE-171, COM-PLY Rep. 6, 20 p. U.S. Dep. Agric., For. Serv., Southeast. For. Exp. Stn., Asheville, N.C.

For group 2, the COM-PLY studs were made from identical materials as group 1 COM-PLY studs except that a semiautomatic factory layup fabrication procedure was used at Champion-International's U.S. plywood plant in South Boston, Virginia. Veneers for the studs were parallel laminated with a phenolic plywood adhesive. Approximately 3,300 COM-PLY studs were fabricated, and 120 were randomly selected for group 2. COM-PLY stud groups 1 and 2 were considered essentially identical since the materials used were equivalent, and high-quality adhesive bonds were used in both groups.

Group 3 consisted of 108 COM-PLY studs that were laboratory fabricated from a commercially available urea formaldehyde door core (6 percent resin, 2 percent wax, Douglas-fir furnish). Stud fabrication consisted of laminating several pairs of 8-foot-long, 1/6-inch-thick southern pine veneers, 1½ inches wide, with a phenol-resorcinol formaldehyde resin. Cores for the studs were ripped 2⅞ inches wide and cut to an 8-foot length. One two-ply veneer laminate was glued to the narrow edge of each core.

Group 4 was made up of sawn lumber studs. For comparison, researchers purchased 140 spruce (*Picea glauca* [Moench] Voss) studs, all stud grade, from a local lumber dealer. No attempt was made to preselect the studs for straightness, grain orientation, or moisture content.

Before testing, all COM-PLY and spruce studs used in these studies were conditioned to a moisture content of 10 ± 2 percent.

EFFECT OF WATER SOAKING ON DIMENSIONAL STABILITY

METHODS

Forty phenolic COM-PLY studs were randomly selected from COM-PLY stud group 2, and 40 stud-grade spruce framing studs were selected from group 4. Twenty COM-PLY and 20 spruce studs were selected for controls. The remaining 20 studs of each type were used in the 24-hour water-soaking test.

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[1] American Plywood Association. 1974. U.S. Products Standard PS 1-74 for construction and industrial plywood with typical APA grade-trademark. 35 p. Am. Plywood Assoc., Tacoma, Wash.

Prior to soaking, the 40 studs were weighed and measured for dimension and distortion using procedures described in the performance standards.[2] The studs were placed in a steel tank and soaked at room temperature for 24 hours. After soaking, all the studs were remeasured while still wet.

RESULTS

The average percentage increase in size after water soaking of the COM-PLY and spruce studs is shown in table 2. The maximum change in dimension of 2.8 percent occurred in the 1½-inch dimension of the COM-PLY studs. In contrast, the spruce studs swelled 1 percent. Both the COM-PLY and the spruce studs swelled about 1 percent in the 3½-inch dimension. Likewise, the change in length (0.03 percent) of both stud types was almost equal.

The data show that the dimensional stability of COM-PLY and spruce studs is about equal after 24 hours of soaking. The magnitude of the changes was small and would not cause any problems in construction.

Table 3 shows the average amount of distortion (warpage) in COM-PLY and spruce studs before and after being exposed 24 hours to water soaking at room temperature. Note that both wet and dry COM-PLY studs were much less distorted than the spruce studs. The COM-PLY studs changed more than the spruce between the dry and wet conditions, but the changes were small. All the distortion exhibited by the two stud types was well within the maximum values considered acceptable by the softwood grading rules.

Table 2.—Average dimensional stability of COM-PLY and spruce studs exposed to 24 hours of water soaking

Stud dimension (inches)	COM-PLY	Spruce
	Percent	
1.5	2.8	1.0
3.5	1.0	.8
93.0	.03	.02

Table 3.—Average distortion of COM-PLY and spruce studs exposed to 24 hours of water soaking

Stud type and moisture condition	Bow	Crook	Twist
		Inch	
COM-PLY:			
Dry	0.063	0.039	0.000
Wet	.093	.142	.011
Spruce:			
Dry	.205	.153	.258
Wet	.179	.128	.248

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[2] Blomquist, Richard F., and others. 1978. Performance standards for composite studs used in exterior walls. U.S. Dep. Agric., For. Serv., Res. Pap. SE-155 (rev.), COM-PLY Rep. 2, 24 p. Southeast. For. Exp. Stn., Asheville, N. C., and U.S. Dep. Housing and Urban Develop., Washington, D. C.

EFFECT OF WATER SOAKING ON DURABILITY

METHODS

Forty group 2 COM-PLY studs and a like number of spruce studs were selected and weighed. Twenty studs of each type were picked for controls, while the remaining studs were stickered and stacked in a steel tank. Room-temperature water was used to soak the 40 studs for 24 hours. After soaking, the wet studs and the controls were conditioned to a moisture content of 10 ± 2 percent.

All studs were tested for bending strength and deflection according to the durability performance standards for COM-PLY studs (*see* footnote 2), except that the end loading was omitted.

RESULTS

Table 4 shows the average strength and deflection properties of COM-PLY and spruce studs before and after 24 hours of water soaking. The strength of COM-PLY and spruce studs was essentially unchanged by the water soaking. The COM-PLY studs were affected only slightly by a 225-pound bending load, showing an increase in deflection (loss of stiffness) of about 2 percent, which was not statistically significant at the 95 percent confidence level. The spruce studs showed a slight (1 percent) decrease in deflection, but this change was also not statistically significant.

Table 4.—Average bending strength and deflection of group 2 COM-PLY and spruce studs exposed to 24 hours of water soaking

Stud type and test condition	Breaking or ultimate load		Deflection at 225-lb load	
	Lb	*Percent*	*Inch*	*Percent*
COM-PLY:				
Control	1,371	100.0	0.311	100.0
Water soaked	1,369	99.9	.317	101.9
Spruce:				
Control	1,631	100.0	.257	100.0
Water soaked	1,613	98.9	.254	98.8

EFFECT OF RELATIVE HUMIDITY ON DIMENSIONAL STABILITY

METHODS

Twenty group 2 COM-PLY studs were randomly selected for this exposure test. In addition, 20 studs were selected from group 4. All studs were weighed and measured for dimension and distortion.

The COM-PLY and spruce studs were stickered and stacked in a 90 percent relative humidity laboratory conditioning room at 75° ± 3° F for 36 months. After exposure, all studs were removed, weighed, and measured for dimension and distortion.

RESULTS

The average dimensional-change data for the COM-PLY and spruce studs are shown in table 5. After 3 years of continuous 90 percent relative humidity exposure, the studs showed more dimensional movement than after the 24-hour water soaking (table 2). This probably occurred because the moisture in the relative humidity exposure had more time to penetrate the complete cross section of both stud types than it did during the soaking procedure.

Table 5.—Average dimensional stability of COM-PLY and spruce studs exposed to 90 percent relative humidity for 36 months

Stud dimension (inches)	COM-PLY	Spruce
	Percent	
1.5	6.3	5.4
3.5	1.8	4.3
93.0	.09	.07

The COM-PLY studs showed the greatest thickness swelling—6.3 percent average increase in the ½-inch dimension, as compared to 5.4 percent average increase in the spruce. In the 3½-inch dimension, ie COM-PLY studs swelled less than the spruce, with 1.8 and 4.3 percent average increases respectively. n the 93-inch dimension, the changes were very small, with the COM-PLY increasing in length slightly nore than the spruce (0.09 percent versus 0.07 percent). None of the stud types exceeded the 8 percent naximum allowable limit permitted by the COM-PLY dimensional stability performance standards (*see* ootnote 2).

Table 6 shows the average distortion of bow, crook, and twist for COM-PLY and spruce studs before nd after being exposed to 90 percent relative humidity for 36 months. Note that COM-PLY studs remained traight even when exposed to long-term high humidity, and only small changes in distortion occurred etween the dry and wet conditions.

The spruce studs reacted differently. As the table shows, the studs were more distorted before they vere exposed to the long-term high humidity than after. When solid-wood studs are cut green, they are sually relatively free from distortion. But when they are dried, differential shrinkage around natural rowth characteristics causes significant distortion. When they are thoroughly wetted again and allowed to emain wet for a long period, swelling will occur in those areas that shrank during drying, and the stud will lmost restore itself to its original undistorted shape.

Table 6.—Average distortion of COM-PLY and spruce studs exposed to 90 percent relative humidity for 36 months

Stud type and moisture condition	Bow	Crook	Twist
		Inch	
COM-PLY:			
Dry	0.101	0.115	0.000
Wet	.113	.115	.033
Spruce:			
Dry	.171	.120	.233
Wet	.128	.067	.057

EFFECT OF RELATIVE HUMIDITY ON DURABILITY

METHODS

For this exposure we used the 20 dimensional-stability COM-PLY studs that had been exposed for 36 nonths at 90 percent relative humidity. The studs were reconditioned to 10 ± 2 percent moisture content along with the 20 group 2 COM-PLY control studs. The conditioned studs were tested under a quarter-point bending load for strength and stiffness, using the testing procedures outlined in the performance standards (*see* footnote 2). Spruce studs were not studied.

RESULTS

Table 7 shows the average bending strength and deflection for the exposed and unexposed COM-PLY studs. Note that 36 months of high relative humidity did not reduce the average strength significantly. Likewise, the deflection at 225 pounds of quarter-point loads was not affected by the long-term storage of the COM-PLY studs at high humidity.

These results indicate that COM-PLY studs exposed to high humidity—such as when a stack of studs is rained on or covered with plastic film and stored on wet soil—will not lose bending strength or stiffness.

Table 7.—Average bending strength and deflection of COM-PLY studs after 90 percent relative humidity (R.H.) exposure for 36 months

Stud type and test condition	Breaking or ultimate load		Deflection at 225-lb load	
	Lb	*Percent*	*Inch*	*Percent*
COM-PLY:				
Control	1,371	100.0	0.311	100
R.H.	1,361	99.3	.311	100

EFFECT OF WEATHERING ON DIMENSIONAL STABILITY

METHODS

Seventy-two conditioned group 1 COM-PLY studs and 20 spruce studs were selected, weighed, and measured for dimension and distortion (*see* footnote 1). Each stud was toe-nailed to the top and bottom plates of a vertical test fence to simulate the outdoor exposure of a newly framed house without roof protection (fig. 1). The test fence was located in an open, gently sloping area.

At 6-month intervals, 18 COM-PLY studs were removed and immediately measured for dimension and distortion. The 20 spruce studs were removed from the test fence and measured immediately after 24 months of weathering. After all studs were measured, they were conditioned to 10 ± 2 percent moisture content for strength evaluations.

RESULTS

Table 8 shows the average dimensional-stability data for phenolic core COM-PLY and spruce studs exposed to weathering. The maximum increase of 2.5 percent in the 1½-inch dimension occurred in the COM-PLY studs after 6 months of exposure. Note that the dimensions increased and decreased with exposure time. The other increases were less, especially in the 3½- and the 93-inch dimensions. In instances where dry weather preceded the removal of the studs, the studs showed less dimensional increase than when wet weather preceded their removal.

At the end of 24 months of exposure, the COM-PLY studs showed an average increase in thickness of 2 percent, while the spruce studs showed no increase in thickness. COM-PLY studs had no linear expansion, while spruce studs showed a slight increase. The zero dimensional change in the 1½- and 3½-inch dimensions for spruce was not unexpected since these studs had the same moisture content after exposure as they did when placed on the fence initially.

Table 9 shows there was more distortion of the COM-PLY than of the spruce studs after 24 months of weathering. The change was small, with the bow distortional change amounting to 0.11 inch. The spruce studs showed little tendency to distort after 24 months of exposure. Note that when the dry spruce studs

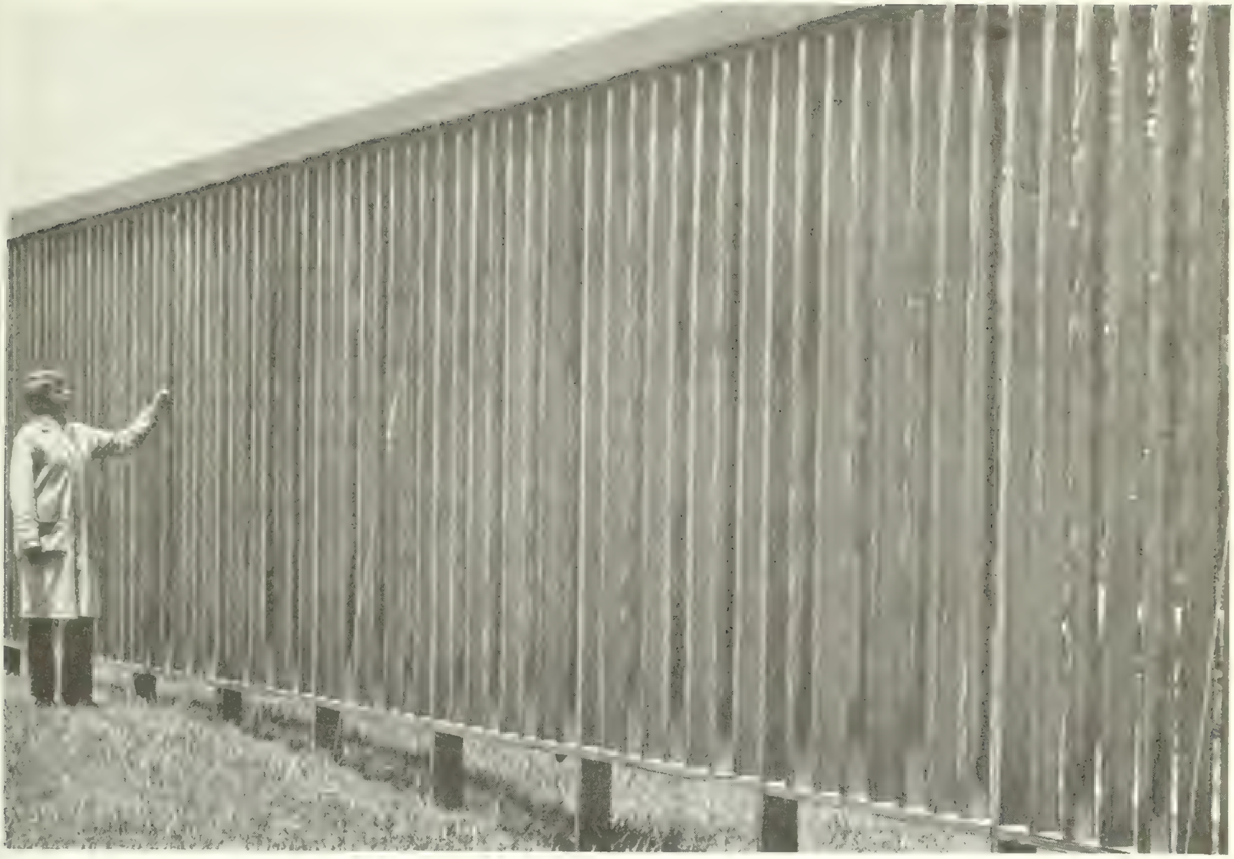

Figure 1.—Weathering of COM-PLY and spruce studs, Athens, Georgia.

Table 8.—Average dimensional stability of studs exposed to weathering

Exposure time (months)	COM-PLY			Spruce		
	1.5-inch	3.5-inch	93.0-inch	1.5-inch	3.5-inch	93.0-inch
	Percent					
6	2.5	0.6	0.04	—	—	—
12	2.1	.3	.00	—	—	—
18	1.3	.2	.00	—	—	—
24	2.0	.3	.00	0.00	0.00	0.03

were placed on the fence, they showed little distortion. Since they were removed at essentially the same moisture content, this lack of distortion was about equal to the initial undistorted condition.

Table 9.—Average distortion of group 1 COM-PLY and spruce studs before and after 2 years of weathering

Stud type and months exposed to weather	Distortion		
	Bow	Crook	Twist
	Inch		
COM-PLY:			
0	0.09	0.04	0.04
24	.20	.11	.11
Spruce:			
0	.12	.17	.11
24	.16	.16	.17

EFFECT OF WEATHERING ON GROUP 1 COM-PLY AND SPRUCE STUD DURABILITY

METHODS

The same 18 COM-PLY and spruce studs that were removed from the test fence at 6-month intervals for dimensional and distortional evaluations and conditioning were also used in the durability tests. They were tested for bending strength and deflection using quarter-point bending according to the performance standards (*see* footnote 2). The exposed spruce studs and the control spruce and COM-PLY studs were tested by the same procedures as the exposed COM-PLY studs.

RESULTS

Table 10 summarizes the average ultimate bending load and deflection data for 24 months of weathering of group 1 COM-PLY and spruce studs. The percentage of initial bending strength and deflection for unexposed studs is also indicated.

Table 10.—The effect of weathering on the strength and deflection of group 1 COM-PLY and spruce studs

Exposure time (months)	Average ultimate load strength				Average deflection of 225-lb load			
	COM-PLY		Spruce		COM-PLY		Spruce	
	Lb	*Percent*	*Lb*	*Percent*	*Inch*	*Percent*	*Inch*	*Percent*
0	1,187	100.0	1,514	100.0	0.353	100.0	0.312	100.0
6	1,099	92.6	—	—	.372	105.3	—	—
12	1,103	94.9	—	—	.377	106.7	—	—
18	1,143	96.3	—	—	.361	102.3	—	—
24	1,029	86.7	1,342	88.7	.388	109.9	.330	105.7

Figure 2 shows the percent of ultimate load strength that was lost versus exposure time for both stud types. Strength losses were small and about the same for both stud types. Although the breaking load for COM-PLY varied somewhat with exposure time, the ultimate loss amounted to only 13 percent. The solid-wood spruce studs, which were tested only once after 24 months of weathering, lost 11 percent of their ultimate bending strength.

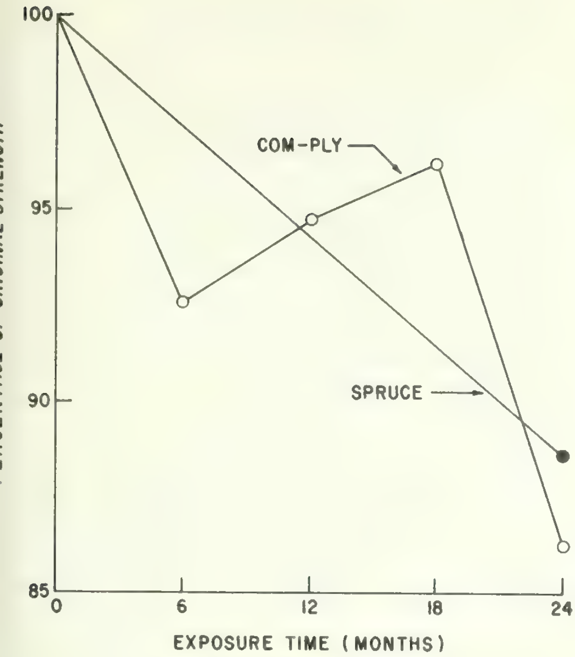

Figure 2.—Ultimate bending strength loss of group 1 COM-PLY and spruce studs exposed to 24 months of weathering.

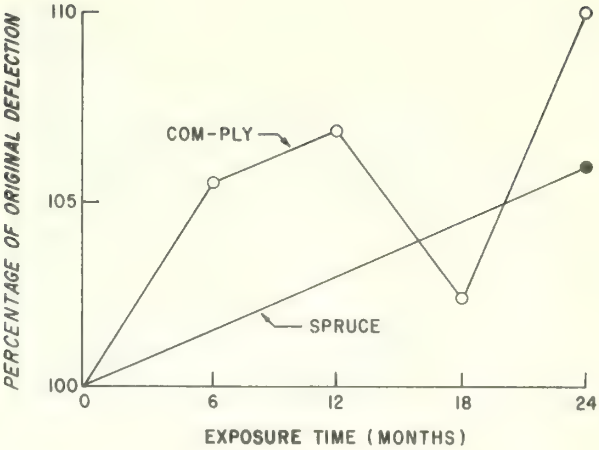

Figure 3.—Deflection at 225-pound load of group 1 COM-PLY and spruce studs after 24 months of weathering.

Figure 3 shows a plot of the deflection change for COM-PLY and spruce studs after weathering 24 months. Again the loss in stiffness (increased deflection) was about the same for both stud types. Note that deflection increased and stiffness decreased as exposure time increased. At the end of 24 months, the average COM-PLY stud deflection increased almost 10 percent, while deflection in the spruce studs increased almost 6 percent after the same period of weathering.

EFFECT OF WEATHERING ON GROUP 3 COM-PLY AND SPRUCE STUD DIMENSIONAL STABILITY

METHODS

One hundred eight group 3 COM-PLY studs made of particleboard containing urea formaldehyde resin binder were weighed and measured for dimension and distortion as required by the performance standards (*see* footnote 2). Each stud was toe-nailed to the top and bottom plates of a test fence in a vertical position. This fence simulated the weathering studs would experience in a framed house without roof protection.

Eighteen group 3 COM-PLY studs were removed after 6, 12, 24, 36, and 48 months and immediately measured for dimension and distortion. They were subsequently conditioned to 10 ± 2 percent moisture content for bending strength and deflection test evaluations.

RESULTS

Table 11 shows the percent increase in size for group 3 COM-PLY studs made with urea resin binder in the particleboard core after weathering for 4 years. The largest change occurred in the 1½-inch dimension.

Six months of weathering increased the thickness of the studs by 3 percent, but increased the 3½-inch dimension by only 0.6 percent. The maximum thickness swelling of 7.3 percent occurred after 24 months of weather exposure. Width and length of the studs changed 1.0 and 0.01 percent, respectively, in 4 years. Dimensional increases for spruce studs were essentially zero for the same exposure periods (table 11). Note that the average thickness and width changes for COM-PLY studs were less after 48 months of exposure than after 24 months of exposure. This decrease in size was attributed to the dry weather which occurred just before the studs were removed from the test fence.

Table 11.—Dimensional stability of group 3 COM-PLY studs after weathering

Stud dimension (inches)	Exposure time (months)				
	6	12	24	36	48
			Percent		
1.5	3.0	2.9	7.3	5.2	4.9
3.5	.6	.4	1.0	.01	.9
93.0	.04	.01	.01	.00	.01

DISTORTION

Table 12 shows the bow and crook distortion of group 3 COM-PLY and spruce studs before and after 24 months of weathering. In addition, the table shows the distortion of another group of group 3 COM-PLY studs before and after 48 months of weathering. Note that bow and crook distortion of both the COM-PLY and the spruce (table 11) changed very little over the 24 months of exposure. The same was true of the group 3 COM-PLY studs exposed to 48 months of weathering.

These distortion data indicate that COM-PLY studs made from urea bonded particleboard do not distort when exposed to the constantly changing moisture environment outdoors. Hence, these COM-PLY studs could be expected to remain straight if they were exposed to weathering during construction.

It is well established that urea formaldehyde resins deteriorate when exposed to prolonged wetting or high temperatures. When urea resin is used for particleboard fabrication, the urea bond breakdown between wood particles results in excessive thickness swelling. Observations made periodically during the weather exposure showed that the tops of the studs did not swell as much as the bottom ends, because the top plate protected the top end of the stud from adverse wetting. However, the bottom plate trapped rain and allowed the water to pool around the ends of the studs, which soaked up water and remained wet long after the rain had stopped. An end coating of wax might have reduced or eliminated the swelling.

Figure 4 shows a plot of the butt end thickness swelling for some of the group 3 COM-PLY studs after being exposed to 6, 12, 24, 36, and 48 months of weathering on the test fence. Note that as the weathering time increased, the butt swelling increased to more than 18 percent after 24 months of exposure. For the next 2 years, the thickness swelling rate slowed to a final thickness swelling of more than 21 percent.

Table 12.—Group 3 COM-PLY stud distortion[1] after outdoor weathering

Exposure time (months)	Type distortion	
	Bow	Crook
	Inch	
0	0.120	0.050
24	.160	.080
0	.112	.052
48	.071	.079

Excessive butt swelling precluded accurate twist measurement.

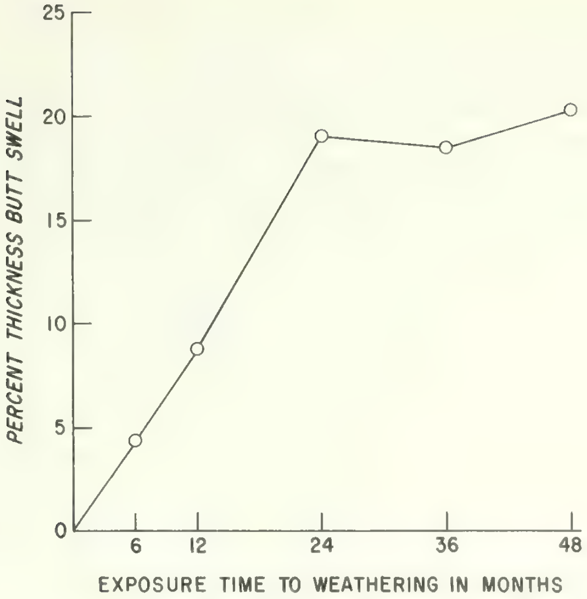

Figure 4.—Butt thickness swelling of group 3 COM-PLY studs after 48 months of weathering.

EFFECT OF WEATHERING ON GROUP 3 COM-PLY STUD DURABILITY

METHODS

The group 3 COM-PLY studs that were removed from the test fence for dimension and distortion measurements were used in the durability evaluations. These studs, as well as 18 group 3 control studs, were tested for bending strength and deflection after 6, 12, 24, 36, and 48 months of outdoor exposure. All bending strength testing followed the procedures outlined in the performance standards (*see* footnote 2).

RESULTS

Table 13 shows the average bending strength and deflection of group 3 COM-PLY studs after 48 months of weathering. Values shown in table 9 are repeated in table 12 for spruce studs after 24 months of exposure.

Table 13.—The effect of weathering on the bending strength and deflection of group 3 COM-PLY and spruce studs

Exposure time (months)	Average ultimate load strength				Average deflection of 225-lb load			
	COM-PLY		Spruce		COM-PLY		Spruce	
	Lb	*Percent*	*Lb*	*Percent*	*Inch*	*Percent*	*Inch*	*Percent*
0	1,116	100.0	1,514	100.0	0.363	100.0	0.312	100.0
6	1,075	96.3	—	—	.362	99.7	—	—
12	1,068	95.7	—	—	.369	101.6	—	—
24	1,045	93.6	1,342	88.7	.415	114.3	.330	105.8
36	1,012	90.7	—	—	.411	113.2	—	—
48	989	88.6	—	—	.349	96.1	—	—

Figure 5 shows a plot of the average loss in ultimate load bending strength for group 3 COM-PLY studs and spruce studs after weathering. The group 3 COM-PLY studs lost strength rather uniformly, with a maximum loss of 11 percent after 48 months. Note that the spruce studs lost about the same amount of strength (11 percent) in 24 months as the group 3 COM-PLY studs lost in 48 months of weathering.

Changes in deflection properties are plotted in figure 6. The average deflections of group 3 COM-PLY studs increased (lost stiffness) steadily with exposure time up to 36 months. However, after 48 months of weathering, the COM-PLY studs showed essentially no gains in deflection compared to the controls. Researchers could not find a plausible explanation for this lack of deflection.

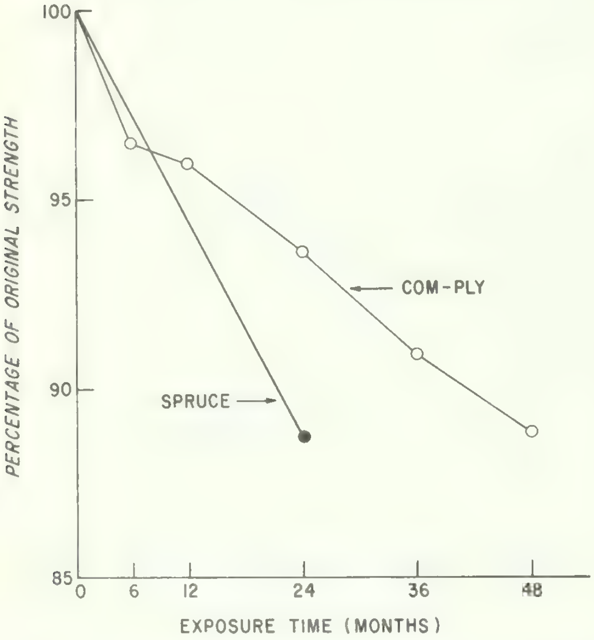

Figure 5.—Change in ultimate load bending strength for group 3 COM-PLY and spruce studs after 48 months of weathering.

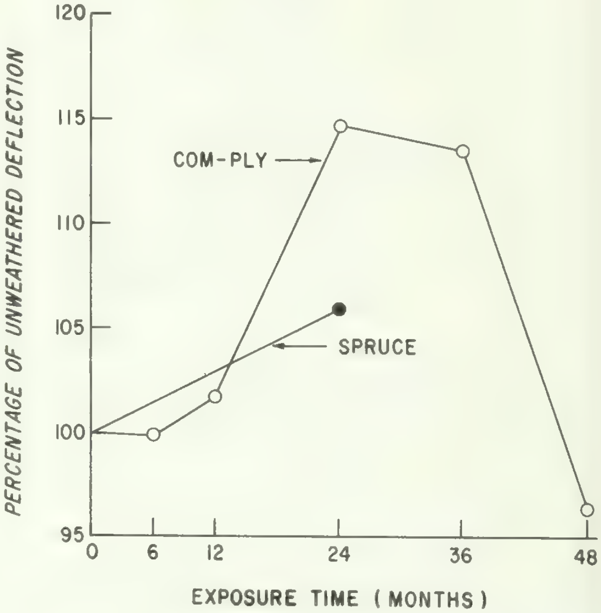

Figure 6.—Deflection at 225-pound bending load for group 3 COM-PLY and spruce studs after weathering.

CONCLUSIONS

These simulated site-exposure studies show that the structural and dimensional properties of phenolic bonded COM-PLY studs remain stable even though the framing may be exposed to water soaking, high relative humidity, or long-term weathering after being framed in a wall. Based on these studies, builders, code officials, and homeowners can rest assured that COM-PLY studs will be at least as durable and dimensionally stable as conventional stud framing in residential construction.

In weathering tests, COM-PLY studs made with particleboard containing urea formaldehyde resin binder retain more strength and stiffness than expected. However, the large dimensional increases of the butt end of the urea COM-PLY studs would preclude their use for wall framing.

Duff, John E.

1980. Dimensional stability and durability of COM-PLY studs exposed to soaking, high humidity, and weathering. USDA For. Serv., Res. Pap. SE-207, COM-PLY Rep. 18, 12 p. Southeast. For. Exp. Stn., Asheville, N.C., and U.S. Dep. Housing and Urban Develop., Washington, D.C.

Exposure of different groups of phenolic-bonded COM-PLY studs to 48 months of weathering, 36 months of high humidity, and 24-hour water soakings resulted in only minor losses in strength and stiffness. Dimensional changes in the COM-PLY studs after these different exposures were small, and no significant distortion occurred.

KEYWORDS: Composite stud exposure, strength loss, stud wetting, distortion.

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SE-208

Predicted Weights and Volumes of Southern Red Oak Trees on the Highland Rim in Tennessee

Alexander Clark III, Douglas R. Phillips,
and Harry C. Hitchcock III

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Conversion factors: English to metric

Multiply	*By*	*To obtain*
Inches	2.540	centimeters
Feet	.3048	meters
Pounds	.4536	kilograms
Cubic feet	.02832	cubic meters
Pounds per cubic foot	16.02	kilograms per cubic meter

All English units of measure in this report can be converted to metric units by multiplying by the appropriate conversion factor listed above.

August 1980
Southeastern Forest Experiment Station
Asheville, North Carolina

Predicted Weights and Volumes of Southern Red Oak Trees on the Highland Rim in Tennessee[1]

by
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ABSTRACT.—Total weights and volumes, above stump, were determined for 29 southern red oak (*Quercus falcata* Michx.) trees 5 to 22 inches d.b.h. growing on the Highland Rim in Tennessee. Equations are presented for predicting green and dry weights and green volume of the total tree and its components using d.b.h. and total height, d.b.h. and height to a 4-inch top, d.b.h. and saw-log merchantable height, and d.b.h. alone. Tables developed from equations show weight and volume of the total tree and its components by d.b.h. and total height classes. Seventy percent of the average tree's green weight was in stem material to a 4-inch top, and 30 percent was in crown material. Total-tree wood had an average specific gravity of 0.604, average moisture content of 74 percent, and average green weight per cubic foot of 66 pounds. The weight of wood and bark averaged 81 pounds per cubic foot of wood for the total tree.

Keywords: *Quercus falcata* Michx., biomass, component proportions, equations, specific gravity, moisture content, weight per cubic foot.

Increasing demands for wood, escalating costs, and the energy shortage have forced forest industries in the South to consider utilizing all parts of trees. Utilizing the total tree above the stump compared to utilizing only the merchantable stem can increase yields from individual hardwood trees by 10 to 65 percent (Clark 1978). Equations for estimating total-tree weight and volume are needed to evaluate and utilize total trees.

This Paper presents green volumes and green and dry weights of above-stump biomass of commercial-size southern red oaks (*Quercus falcata* Michx.) growing in an uneven-aged stand in south-central Tennessee. Equations and yield tables predict weight and volume of the total tree and its components (wood, bark, saw logs, stem, and crown). Wood and bark specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components.

PROCEDURE

Field

A stratified random sample of 29 southern red oak trees was selected from a natural, fully stocked, uneven-aged stand of mixed oaks. The stand had an average site index for southern red oak of 70 and was located on the Highland Rim in Coffee County, Tennessee. Four trees were selected from each of seven d.b.h. classes at 2-inch intervals from 6 to 18 inches, and one tree was chosen from the 22-inch class. Form class of the sawtimber trees ranged from 70 to 82 and averaged 75. The trees sampled ranged from 37 to 100 years of age and averaged 62 years. Means and ranges of tree measurements are shown in table 1.

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[1] This study was conducted in cooperation with and through the financial assistance of the Division of Land and Forest Resources, Tennessee Valley Authority, Norris, Tennessee. Cooperation and assistance were also received from the Arnold Engineering Development Center, Tullahoma, Tennessee.

Table 1.—Means and ranges in dimensions of southern red oak trees sampled in Coffee County, Tennessee, by d.b.h. class

D.b.h. class (inches)	Sample trees	D.b.h.		Total height		Height to 4-inch d.i.b. top		Height to saw-log merchantable top[a]		D.o.b. at saw-log merchantable top	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
	Number	...... *Inches*		....	....	*Feet*	....	....	....	...... *Inches*	
6	4	6.2	5.4– 6.7	54	53–55	19	13–25	—	—	—	—
8	4	8.3	7.7– 8.7	62	56–66	37	28–43	—	—	—	—
10	4	9.9	9.5–10.2	72	66–80	45	39–54	—	—	—	—
12	4	12.0	11.3–12.8	70	68–72	48	45–52	21	18–26	9.5	8.6–10.6
14	4	14.6	14.1–14.9	71	69–74	51	48–55	21	18–28	11.8	11.4–12.5
16	4	16.1	15.2–16.7	76	72–77	55	54–56	22	19–27	13.4	12.2–14.6
18	4	18.2	17.5–18.6	80	77–84	61	57–65	32	27–35	13.9	12.3–14.8
20	0	—	—	—	—	—	—	—	—	—	—
22	1	22.0	—	81	—	63	—	23	—	16.9	—
All classes	29	12.5	5.4–22.0	70	53–84	45	13–65	24	18–35	12.4	8.6–16.9

[a] Height to 8-inch d.i.b. or saw-log merchantable top.

Trees were felled and limbed during the winter, and the main stem of each tree was bucked into merchantable saw logs and pulpwood. Saw logs 8 to 18 feet long were cut from the main stem to an 8-inch d.i.b. top or to a degrading quality indicator such as large knots. Stem d.o.b. to the saw-log top averaged 12.4 inches (table 1). All material between the saw-log merchantable top and the 4-inch d.i.b. top was classed as "pulpwood." All trees had a discernible main stem to a 4-inch top. Material between the 4- and 2-inch d.i.b. top was classed as "topwood." The crown was cut up and separated into four categories: (extra large branches (≥ 4.0 inches d.o.b), (2) large branches (≥ 2.0 and < 4.0 inches d.o.b.), (3) medium branches (≥ 0.6 inches and < 2.0 inches d.o.b.), and (4) small branches (≤ 0.5 inches d.o.b.). The tip of the stem (2 inches to top) was included as branch material in the analysis. Dead branches were cut from the bole and weighed separately. All crown material and pulpwood were weighed to the nearest quarter of a pound. Saw logs were weighed individually to the nearest pound.

Disks were removed from the butt of each sawtimber tree (trees ≥ 11.0 inches d.b.h.); at each saw-log bucking point; at the points where d.i.b. measured 8, 6, 4, and 2 inches; and from branches randomly selected from each branch-size category. In pulpwood-size trees (trees 5.0 to 10.9 inches d.b.h.), disks were cut from the butt of each tree, at quarter points to a 4-inch top, and where d.i.b. measured 2.0 inches. Each disk was sealed in a polyethylene bag for subsequent laboratory determinations of moisture content, specific gravity, and bark percent.

Laboratory

Specific gravity was computed on a green-volume and ovendry-weight basis. Moisture content was computed on an ovendry-weight basis after samples were dried to a constant weight at 103° C. Percentage of bark was determined from disks on a green-weight basis. Moisture content, specific gravity, and percentage of bark in the stem, branches, and the total tree were calculated by weighting disk values in proportion to the volume of the component they represented. Weighted values for moisture content were used to convert component green weight to ovendry weight.

Green weights per cubic foot of wood and bark were calculated from weighted values for specific gravity and moisture content with the equation:

Green weight per cubic foot

$$= \left[1 + \frac{\text{M.C.}}{100}\right] \times (\text{S.G.}) \times (\text{C}) \qquad (1)$$

where:

M.C. = weighted moisture content in percent
S.G. = weighted specific gravity,
C = 62.4 pounds (weight of water per cubic foot).

Cubic-foot volumes of green wood and bark were computed by dividing component weight by its green weight per cubic foot. Total green cubic-foot volume (wood and bark combined) was computed by adding the green volume of wood to the green volume of bark.

Analysis

Linear regression equations were developed to predict green and dry weights and green volumes of wood and bark in the total tree and its components. Independent variables were: diameter at breast height (D), total height (Th), saw-log merchantable height (Mh), and height to a 4-inch top (H4), both separately and in various combinations.

Grouping the data into D^2Th classes and plotting the variance of Y over D^2 and D^2Th indicated that the variance of predicted weights and volumes increased with increasing D^2 and D^2Th. A logarithmic transformation (to the base 10) was used to obtain a relatively homogeneous variance, which is assumed in regression analysis. Thus, regression equations for tree and component weights and volumes were calculated using the equations:

$$\text{Log } Y = b_0 + b_1 \text{ Log } X + \epsilon \qquad (2)$$

$$\text{Log } Y = b_0 + b_1 \text{ Log } X_1 + b_2 \text{ Log } X_2 + \epsilon \qquad (3)$$

where:

Y = weight or volume of component,
X = D^2, D^2Th, D^2H4, or D^2Mh,
X_1 = D^2
X_2 = Th, H4, or Mh,
ϵ = sampling error,
b_i = regression coefficients.

When logarithmic estimates are converted back to original units, they are biased downward because the antilogarithm of an estimated mean gives the geometric rather than the arithmetic mean (Cunia 1964). To account for this bias, a correction factor was computed using a procedure described by Baskerville (1972) and applied to each equation. The forms of the equations, including the correction factor, are:

$$Y = 10^{b_0 + b_1 \log X + \frac{S^2_{y \cdot x}}{2}} \qquad (4)$$

and

$$Y = 10^{b_0 + b_1 \text{Log} X_1 + b_2 \log X_2 + \frac{S^2_{y \cdot x}}{2}} \qquad (5)$$

where:

$S^2_{y \cdot x}$ = error mean square from regression analysis

Equations (4) and (5) were simplified to:

$$Y = aX^{b_1} \qquad (6)$$

and

$$Y = aX_1^{b_1}X_2^{b_2} \qquad (7)$$

where:

$$a = 10^{b_0} + \frac{S^2_{y \cdot x}}{2}$$

SAMPLE TREE CHARACTERISTICS

Total Tree

Green weight of the trees sampled ranged from an average of 279 pounds for 6-inch trees to 7,681 pounds for the 22-inch tree. Assuming the trees were composed solely of wood, bark, and water, 41 percent of their green weight was water; 46 percent was wood; and 13 percent was bark. The proportions of total-tree weight in wood and bark did not vary with tree size. The proportion of tree weight in bark ranged from 19 to 21 percent, averaging 19 percent on a green basis. This is slightly higher than the averages reported for northern red oak (*Q. rubra* L.) (15 percent) (Clark and others, in press) and scarlet oak (*Q. coccinea* Muenchh.) (16 percent) (Clark and others, in press). Wood made up an average of 78 percent of total-tree dry weight, and bark 22 percent.

The proportion of green weight in crown material (all live branches and topwood) ranged from 17 to 44 percent but did not vary consistently with tree size. The proportion of green weight in the stem to a 4-inch top averaged 70 percent; the proportion in crowns averaged 30 percent. Sixty-eight percent of the tree's dry weight was in stem material and 32 percent was in crown material.

The proportion of total-tree green weight in dead branches ranged from 0 to 1 percent and averaged 0.8 percent.

The green and dry weights of all wood and bark in the tree and the distribution of wood and bark throughout the tree are presented in tables 2 and 3. On the average, pulpwood-size trees had 73 percent of their total green wood weight in the stem to a 4-inch d.i.b. top and 27 percent in the crown. Sawtimber trees on the average had 72 percent of their green wood weight in the stem to a 4-inch top and 28 percent in the crown. Forty-six percent of their green wood weight was saw-log material and 26 percent was pulpwood.

Wood and bark are not distributed evenly throughout the tree. For example, the stem to a 4-inch top of the average sawtimber tree contained 72 percent of all the green wood in the tree but only 59 percent of the bark. On the other hand, branches contained 28 percent of the green wood and 41 percent of the bark. The proportion of green wood in branches generally increased with increasing tree size, ranging from 15 percent in pulpwood trees to 27 percent in sawtimber trees. The proportion of total-tree green bark weight in branches also increased with tree size, ranging from 22 percent in pulpwood trees to 40 percent in sawtimber trees.

Table 2.—Average green and dry weight of wood in the total tree and its distribution in the main stem[a] and live branches in southern red oak trees

D.b.h. class (inches)	Average total height	Sample trees	Total-tree wood weight	Proportion of wood in—								
				Main stem				Live branches (inches d.o.b.)				
				Saw-log[b]	Pulp-wood[c]	Top-wood	Total stem	≥ 4	< 4 & ≥ 2	< 2 & > 0.5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	....	....	....	....	*Percent*	....	....	....	....
				GREEN PULPWOOD								
6	54	4	275	—	57	24	81	—	5	12	2	19
8	62	4	584	—	77	7	84	—	2	12	2	16
10	72	4	845	—	85	5	90	—	4	6	1	10
Average	—	—	568	—	73	12	85	—	3	10	2	15
				GREEN SAWTIMBER								
12	70	4	1,650	53	28	2	83	3	8	7	1	17
14	71	4	2,475	42	28	1	71	7	12	9	1	29
16	76	4	3,339	43	29	1	73	8	11	7	1	27
18	80	4	4,576	52	19	1	72	12	9	6	1	28
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	6,250	39	28	1	68	14	8	9	1	32
Average	—	—	3,201	46	26	1	73	10	9	7	1	27
				DRY PULPWOOD								
6	54	4	160	—	56	24	80	—	8	14	3	21
8	62	4	350	—	76	7	82	—	2	13	2	17
10	72	4	488	—	84	6	89	—	6	7	1	11
Average	—	—	333	—	72	12	84	—	5	10	2	16
				DRY SAWTIMBER								
12	70	4	949	52	28	2	82	3	8	8	1	18
14	71	4	1,415	40	28	1	69	8	12	10	1	31
16	76	4	1,896	41	28	1	71	8	12	8	1	29
18	80	4	2,559	50	19	1	70	12	10	7	1	30
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	3,530	37	27	1	65	15	9	10	1	35
Average	—	—	1,812	45	25	1	71	11	11	8	1	31

[a] Main stem to 2-inch d.i.b. top.

[b] Saw logs to 8-inch d.i.b. or saw-log merchantable top.

[c] Pulpwood in stem from butt or saw-log top to 4-inch d.i.b. top.

Table 3.—Average green and dry weight of bark in the total tree and its distribution in the main stem[a] and live branches in southern red oak trees

				Proportion of bark in—								
				Main stem				Live branches (inches d.o.b.)				
D.b.h. class (inches)	Average total height	Sample trees	Total-tree bark weight	Saw-log[b]	Pulp-wood[c]	Top-wood	Total stem	≥ 4	< 4 & ≥ 2	< 2 & > 0.5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				GREEN PULPWOOD								
6	54	4	66	—	52	23	74	—	6	18	4	26
8	62	4	140	—	69	7	76	—	3	17	4	24
10	72	4	215	—	77	7	84	—	6	10	2	16
Average	—	—	140	—	66	12	78	—	5	14	3	22
				GREEN SAWTIMBER								
12	70	4	394	42	28	3	73	4	12	11	2	26
14	71	4	640	33	24	1	59	8	16	13	2	41
16	76	4	765	34	24	1	60	10	15	12	3	40
18	80	4	1,041	40	17	1	57	15	14	11	2	29
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	1,431	32	24	1	56	17	12	12	3	44
Average	—	—	752	37	22	1	60	13	14	11	2	40
				DRY PULPWOOD								
6	54	4	42	—	55	21	76	—	5	17	5	24
8	62	4	96	—	71	7	77	—	2	16	4	22
10	72	4	149	—	78	7	86	—	5	9	2	14
Average	—	—	97	—	68	12	80	—	4	13	3	20
				DRY SAWTIMBER								
12	70	4	273	43	29	3	75	4	12	10	2	25
14	71	4	439	34	25	1	60	9	16	12	2	40
16	76	4	521	35	25	1	61	10	15	11	2	39
18	80	4	709	41	17	1	58	15	14	10	2	41
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	982	33	25	1	58	18	11	11	2	42
Average	—	—	515	37	23	1	61	13	14	10	2	39

[a] Main stem to 2-inch d.i.b. top.

[b] Saw logs to 8-inch d.i.b. or saw-log merchantable top.

[c] Pulpwood in stem from butt or saw-log top to 4-inch d.i.b. top.

Stem Components

The main stem to a 4-inch top had 84 percent of its green weight in wood and 16 percent in bark, while 80 percent of the dry stem weight was wood and 20 percent bark. The proportion of stem weight in wood and bark did not vary with tree size.

Crown Components

The proportion of crown green weight in bark ranged from 21 to 29 percent but did not vary consistently with tree size. The proportion of crown green weight in wood averaged 74 percent and in bark it averaged 26 percent. The proportions averaged 72 and 27 percent, respectively, on a dry basis. For branches, the proportion of green weight in bark increased with decreasing branch size. Branches ≥ 4 inches had 23 percent of their weight in bark, while branches ≤ 0.5 inches d.o.b. had 33 percent of their weight in bark. Dead branches comprised 3 percent of total crown green weight.

The change in distribution of crown materials with increasing tree size is shown in figure 1.

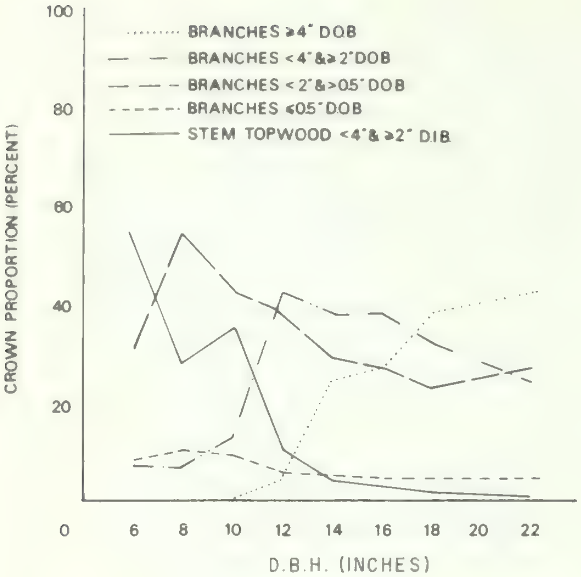

Figure 1.—Proportions of southern red oak crown green weight in topwood and branches, by d.o.b.-size classes.

Physical Properties

Wood and bark specific gravity, moisture content, and green weight per cubic foot for the total tree and its components are presented in table 4. Wood specific gravity and moisture content did not vary significantly with tree size. Specific gravity averaged 0.604 for the total tree and 0.587 for the total stem—higher than the average of 0.52 reported for southern red oak stem wood (Forest Products Laboratory 1974). Branches had the highest specific gravity, averaging 0.659, and saw-log wood the lowest, averaging 0.587. Average moisture content of wood ranged from 60 percent in the branches to 81 percent in saw logs and averaged 74 percent for all wood in the tree. Green weight per cubic foot averaged 65 pounds in the main stem and 66 pounds in the branches and total tree.

Specific gravity of bark was lowest in branches (0.606) and highest in the pulpwood section of the main stem (0.668). Bark specific gravity in the total tree averaged 0.642—higher than the corresponding wood specific gravity value. Bark moisture content for the total tree averaged 47 percent, which was lower than the corresponding value for wood. Branch bark moisture content was the highest, averaging 55 percent, and pulpwood bark was the lowest, averaging 43 percent. Average green bark weight per cubic foot ranged from 58 pounds for branches to 62 pounds for the

Table 4.—Average wood and bark specific gravity, moisture content, and green weight per cubic foot for southern red oak trees and tree components

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	*Pounds*
	WOOD		
Total tree	0.604 ± 0.021	74 ± 5.8	66 ± 1.5
Stem (butt to 4-inch d.i.b. top)	.587 ± .022	79 ± 7.0	65 ± 1.5
Saw log (butt to 8-inch d.i.b. top)	.587 ± .022	81 ± 6.6	66 ± 1.7
Pulpwood (8- to 4-inch d.i.b. top)	.602 ± .023	72 ± 4.8	65 ± 1.8
Topwood (4- to 2-inch d.i.b. top)	.633 ± .033	65 ± 3.7	65 ± 2.6
Branches	.659 ± .024	60 ± 4.2	66 ± 1.8
	BARK		
Total tree	0.642 ± 0.035	47 ± 4.7	59 ± 2.6
Stem (butt to 4-inch d.i.b. top)	.652 ± .042	44 ± 3.9	58 ± 3.0
Saw log (butt to 8-inch d.i.b. top)	.651 ± .046	44 ± 4.3	58 ± 3.1
Pulpwood (8- to 4-inch d.i.b. top)	.668 ± .042	43 ± 4.0	60 ± 3.5
Topwood (4- to 2-inch d.i.b. top)	.667 ± .031	48 ± 7.0	62 ± 3.5
Branches	.606 ± .044	55 ± 5.1	58 ± 3.2

topwood section and averaged 59 pounds for the total tree.

The weight of wood and bark per unit volume of wood is a useful factor for estimating the volume of wood in a tree or its components when weight with bark is known. The average green weight of wood and bark per cubic foot of wood was 81 pounds for the total tree and 79 pounds for the stem (table 5). For branch material, the green weight of wood and bark per cubic foot of wood averaged 88 pounds and was considerably higher than the average for the main stem, because branches contain 38 percent more of their weight in bark.

Green weight per cubic foot of wood and bark combined averaged 64 pounds for the total tree, stem, and branch material (table 5).

and D^2H4 as the independent variable. When D^2 and Mh were used as separate variables in equation (3), the coefficient of determination (R^2) increased 15 to 20 percent and the standard error was reduced. Thus, the two-variable model was used when D^2 and Mh were the independent variables.

All independent variable combinations were good predictors of weights and volumes, but equations using D^2Th were the best for total-tree values. These equations had slightly higher coefficients of determination and slightly lower standard errors of estimates than the equations using D^2, D^2H4, or $D^2 + Mh$.

Equations using $D^2 + Mh$ were the best estimators of saw-log merchantable stem weight and volume, while equations using D^2H4 were the best predictors of stem weight and volume to a 4-inch top. When average tree heights and stem taper for d.b.h. classes are similar to those of our sample trees, the equations using d.b.h. alone will result in good estimates of tree weight and volume. However, when average tree heights by d.b.h. classes are different, the equations that include a height variable should be applied directly or used to develop local weight-volume tables based on d.b.h. alone.

Table 5.—Average green weight of wood and bark per cubic foot of wood and average green weight of wood and bark per cubic foot of wood and bark for southern red oak trees and tree components

Tree component	Average and standard deviation	
	Green weight of wood & bark per cubic foot of wood	Green weight of wood & bark per cubic foot of wood & bark
	Pounds	
Total tree	81 ± 1.9	64 ± 1.5
Stem (butt to 4-inch d.i.b. top)	79 ± 1.9	64 ± 1.6
Saw log (butt to 8-inch d.i.b. top)	79 ± 1.8	65 ± 1.3
Pulpwood (8- to 4-inch d.i.b. top)	82 ± 3.8	64 ± 1.8
Topwood (4- to 2-inch d.i.b. top)	87 ± 6.6	64 ± 2.6
Branches	88 ± 4.3	64 ± 1.6

PREDICTION EQUATIONS

A series of equations was developed to predict weights and volumes of total trees and their components. Since heights of trees are measured to different top limits by various organizations, equations were developed using D^2 alone and in combination with Th, H4, and Mh separately and combined as independent variables. When D^2 and Th or D^2 and H4 were used, the one-variable equation (2) and the two-variable equation (3) predicted total-tree and component weights and volumes equally well. The use of height as a separate variable did not improve the coefficient of determination or reduce the standard error. Thus, the single-variable model was used to predict tree weight and volume when using D^2, D^2Th,

Appendix tables 6 and 7 present equations for predicting all weights and volumes measured from D^2Th. Appendix tables 8 and 9 present equations that use D^2, D^2H4, and $D^2 + Mh$ to predict the green weights of wood and bark and volumes of wood for selected tree components of greatest interest. The Appendix also describes a method for placing confidence limits on predictions made with the equations.

A complete list of equations based on D^2, D^2H4, and D^2Mh for predicting the green and dry weights and volumes of wood and bark in all tree components listed in tables 6 and 7 is available from the authors at the Southeastern Forest Experiment Station, Forestry Sciences Laboratory, Carlton Street, Athens, Georgia 30602. Also available are uncorrected sums and sums of squares and their cross products for the independent and dependent variables listed in tables 6 and 7. These data make it possible to compare and combine equations statistically. They also allow for the addition of observations and for computation of error terms.

BIOMASS TABLES

Equations based on D^2Th from tables 6 and 7 were used to develop tables of biomass weight and volume. Tables 10-13 show predicted green weight of wood and bark and wood alone in the total tree, the saw-log stem to an 8-inch d.i.b. or saw-log merchantable top, the stem to a 4-inch d.i.b. top, and the crown. Tables 14–17 show predicted green volumes of wood and bark and wood alone in the total tree and its components. The predicted weight or volume of bark in a tree or component can be estimated by subtracting the value in the table for wood alone from the corresponding value in the table for wood and bark combined.

Similar-sized trees may vary in weight and volume because of differences in crown size, stem taper, and weight per cubic foot. Therefore, the equations and tables should be applied only to trees growing in natural, fully stocked stands which have stem taper rates and weights per cubic foot similar to the trees sampled.

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APPENDIX

Table 6.—Regression equations for estimating above-stump green and dry weights of the total tree and its components for southern red oak trees 5 to 22 inches d.b.h., using d.b.h. and total height as independent variables

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)[c]	Number trees sampled (N)
Total tree (excluding foliage):				
Green weight	$Y = 0.06632\,(D^2Th)^{1.11245}$	0.98	0.0538	29
Dry weight	$Y = 0.04381\,(D^2Th)^{1.10112}$	.98	.0560	29
All wood in tree:				
Green weight	$Y = 0.05262\,(D^2Th)^{1.11420}$	.98	.0571	29
Dry weight	$Y = 0.03565\,(D^2Th)^{1.09624}$	.98	.0623	29
All bark in tree:				
Green weight	$Y = 0.01378\,(D^2Th)^{1.10452}$	.98	.0540	29
Dry weight	$Y = 0.00834\,(D^2Th)^{1.11743}$	.98	.0545	29
Wood and bark in stem from stump to saw-log merchantable top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.23227\,(D^2Th)^{0.90557}$	.73	.1020	17
Dry weight	$Y = 0.17670\,(D^2Th)^{0.87631}$	.71	.1038	17
Wood in stem from stump to saw-log merchantable top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.16578\,(D^2Th)^{0.92239}$	.73	.1044	17
Dry weight	$Y = 0.12366\,(D^2Th)^{0.89071}$	.70	.1086	17
Bark in stem from stump to saw-log merchantable top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.08607\,(D^2Th)^{0.81733}$	.70	.1000	17
Dry weight	$Y = 0.06024\,(D^2Th)^{0.81841}$	.70	.1002	17
Wood and bark in stem from stump to 8-inch d.i.b. top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.08870\,(D^2Th)^{1.03856}$	.96	.0404	17
Dry weight	$Y = 0.06746\,(D^2Th)^{1.00930}$	.95	.0421	17
Wood in stem from stump to 8-inch d.i.b. top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.06330\,(D^2Th)^{1.05538}$	.95	.0446	17
Dry weight	$Y = 0.04720\,(D^2Th)^{1.02370}$	.94	.0503	17
Bark in stem from stump to 8-inch d.i.b. top (trees $\geq$ 11.0 inches d.b.h.):				
Green weight	$Y = 0.03327\,(D^2Th)^{0.95033}$	.95	.0427	17
Dry weight	$Y = 0.02302\,(D^2Th)^{0.95140}$	.95	.0426	17
Wood and bark in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.03062\,(D^2Th)^{1.15873}$	.98	.0607	29
Dry weight	$Y = 0.02132\,(D^2Th)^{1.13946}$	.98	.0665	29
Wood in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.02324\,(D^2Th)^{1.16832}$	.98	.0604	29
Dry weight	$Y = 0.01627\,(D^2Th)^{1.14398}$	.98	.0681	29
Bark in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.00812\,(D^2Th)^{1.11044}$	.97	.0787	29
Dry weight	$Y = 0.00519\,(D^2Th)^{1.11995}$	.97	.0825	29

Continued

Table 6.—Regression equations for estimating above-stump green and dry weights of the total tree and its components for southern red oak trees 5 to 22 inches d.b.h., using d.b.h. and total height as independent variables—Continued

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)[c]	Number trees sampled (N)
Wood and bark in crown (all branches and topwood < 4 inches d.i.b.):				
Green weight	$Y = 0.02596\ (D^2Th)^{1.07671}$	.83	.1930	29
Dry weight	$Y = 0.01531\ (D^2Th)^{1.08312}$	.83	.1904	29
Wood in crown (all branches and topwood < 4 inches d.i.b.):				
Green weight	$Y = 0.02292\ (D^2Th)^{1.05855}$	.80	.2053	29
Dry weight	$Y = 0.01417\ (D^2Th)^{1.05815}$	.80	.2035	29
Bark in crown (all branches and topwood < 4 inches d.i.b.):				
Green weight	$Y = 0.00376\ (D^2Th)^{1.13674}$	.88	.1615	29
Dry weight	$Y = 0.00197\ (D^2Th)^{1.16047}$	.89	.1627	29
Wood and bark in crown ≥ 2.0 inches d.o.b.:				
Green weight	$Y = 0.00394\ (D^2Th)^{1.22418}$	.77	.2584	29
Dry weight	$Y = 0.00220\ (D^2Th)^{1.23551}$	.78	.2541	29
Wood in crown ≥ 2.0 inches d.o.b.:				
Green weight	$Y = 0.00399\ (D^2Th)^{1.19380}$	.75	.2662	29
Dry weight	$Y = 0.00232\ (D^2Th)^{1.19815}$	.76	.2633	29
Bark in crown ≥ 2.0 inches d.o.b.:				
Green weight	$Y = 0.00033\ (D^2Th)^{1.33341}$	.83	.2378	29
Dry weight	$Y = 0.00017\ (D^2Th)^{1.36417}$	.83	.2375	29
Wood and bark in dead branches:				
Green weight	$Y = 0.00214\ (D^2Th)^{0.96298}$	.44	.4460	25
Dry weight	$Y = 0.00143\ (D^2Th)^{0.96617}$	.44	.4533	25

[a] $Y = b_0\ (D^2Th)^{b_1}$

where:

Y = component weight in pounds,

D = d.b.h. in inches,

Th = total tree height in feet,

b_0, b_1 = regression coefficients.

[b] Standard error in Log_{10} form.

[c] Additional statistics for computation of confidence intervals:

$\Sigma(x-\bar{x})^2 = 4.1055$ and $\bar{x} = 3.9785$ for equations based on 29 trees and

$\Sigma(x-\bar{x})^2 = 0.5235$ and $\bar{x} = 4.2471$ for equations based on 17 trees.

Table 7.—Regression equations for estimating above-stump green cubic-foot volume of the total tree and its components for southern red oak trees 5 to 22 inches d.b.h., using d.b.h. and total height as independent variables

Cubic-foot volume (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)[c]	Number trees sampled (N)
Total tree (excluding foliage):				
Wood	$Y = 0.000913 (D^2Th)^{1.10025}$	0.98	0.0559	29
Bark	$Y = 0.000318 (D^2Th)^{1.07124}$	.98	.0524	29
Wood & bark	$Y = 0.001220 (D^2Th)^{1.09436}$	.99	.0524	29
Stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.002805 (D^2Th)^{0.91079}$	.74	.0998	17
Bark	$Y = 0.001801 (D^2Th)^{0.79487}$	.68	.1015	17
Wood & bark	$Y = 0.004113 (D^2Th)^{0.89093}$	.74	.0985	17
Stem from stump to 8-inch d.i.b. top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.001072 (D^2Th)^{1.04378}$	.96	.0422	17
Bark	$Y = 0.000688 (D^2Th)^{0.92787}$	.93	.0461	17
Wood & bark	$Y = 0.001570 (D^2Th)^{1.02392}$	.96	.0393	17
Stem from stump to 4-inch d.i.b. top:				
Wood	$Y = 0.000389 (D^2Th)^{1.15821}$	.98	.0606	29
Bark	$Y = 0.000221 (D^2Th)^{1.05965}$	.97	.0775	29
Wood & bark	$Y = 0.000567 (D^2Th)^{1.13994}$	.98	.0611	29
Crown material (all branches and top-wood < 4 inches d.i.b. excluding foliage):				
Wood	$Y = 0.000415 (D^2Th)^{1.03977}$	.79	.2051	29
Bark	$Y = 0.000068 (D^2Th)^{1.12860}$	.89	.1580	29
Wood & bark	$Y = 0.000465 (D^2Th)^{1.06191}$	.82	.1905	29
Crown material ≥ 2.0 inches d.o.b.:				
Wood	$Y = 0.000074 (D^2Th)^{1.17306}$	.75	.2657	29
Bark	$Y = 0.000004 (D^2Th)^{1.35751}$	.83	.2396	29
Wood & bark	$Y = 0.000068 (D^2Th)^{1.21332}$	.77	.2575	29

[a] $Y = b_0 (D^2Th)^{b_1}$

where:

Y = component volume in cubic feet.
D = d.b.h. in inches,
Th = total tree height in feet,
b_0, b_1 = regression coefficients.

[b] Standard error in $\log_{10}$ form.

[c] Additional statistics for computation of confidence intervals:
$\Sigma(x-\bar{x})^2 = 4.1055$ and $\bar{x} = 3.9785$ for equations based on 29 trees and
$\Sigma(x-\bar{x})^2 = 0.5235$ and $\bar{x} = 4.2471$ for equations based on 17 trees.

Table 8.—Regression equations for estimating the above-stump wood and bark green weight for southern red oak trees 5 to 22 inches d.b.h. and tree components, using d.b.h., d.b.h. and height to 4-inch top, and d.b.h. and saw-log merchantable height as independent variables

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)	Sample mean of x[b] ($\bar{x}$)	Corrected sums of squares for x[b] $\Sigma(x-\bar{x})^2$	Number trees sampled (N)
Wood and bark in total tree, above stump						
	$Y = 3.08334 (D^2)^{1.28986}$	0.99	0.0506	2.1384	3.0593	29
	$Y = 1.02421 (D^2H4)^{0.85852}$	.96	.0825	3.7728	6.7502	29
	$Y = 4.11999 (D^2)^{1.06916}(Mh)^{0.29694}$	.95	.0430	—	—	17
Wood and bark in stem from stump to saw-log merchantable top						
	$Y = 6.55544 (D^2)^{1.00903}$	.68	.1110	2.3749	.3935	17
	$Y = 0.68801 (D^2H4)^{0.82142}$	.74	.1014	4.1079	.6390	17
	$Y = 0.99043 (D^2)^{0.72002}(Mh)^{1.09571}$	.96	.0394	—	—	17
Wood and bark in stem from stump to 4-inch d.i.b. top						
	$Y = 1.71928 (D^2)^{1.33801}$	.98	.0706	2.1384	3.0593	29
	$Y = 0.46633 (D^2H4)^{0.90814}$	.99	.0407	3.7728	6.7502	29
	$Y = 6.56902 (D^2)^{0.90917}(Mh)^{0.31723}$	.96	.0330	—	—	29
Wood and bark in crown (all branches and topwood < 4-inches d.i.b.)						
	$Y = 0.98186 (D^2)^{1.26423}$	.85	.1801	2.1384	3.0593	29
	$Y = 0.47085 (D^2H4)^{0.80376}$	.76	.2281	3.7728	6.2502	29
	$Y = 0.09298 (D^2)^{1.51128}(Mh)^{0.33387}$	.81	.1312	—	—	17

[a] $Y = a(D^2)^{b_1}$ or $Y = a(D^2H4)^{b_1}$ or $Y = a(D^2)^{b_1}(Mh)^{b_2}$

where:

Y = component weight in pounds,
D = d.b.h. in inches,
H4 = tree height to 4-inch d.i.b. top in feet,
Mh = saw-log merchantable height in feet,
a, b_1, b_2 = regression coefficients.

[b] Log_{10} form.

Table 9.—Regression equations for estimating the above-stump wood volume of southern red oak trees 5 to 22 inches d.b.h. and tree components, using d.b.h., d.b.h. and height to a 4-inch top, and d.b.h. and saw-log merchantable height as independent variables

Cubic-foot volume (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)	Sample mean of x[b] ($\bar{x}$)	Corrected sums of squares for x[b] $\Sigma(x-\bar{x})^2$	Number trees sampled (N)
Wood in total tree, above stump						
	$Y = 0.04080 (D^2)^{1.27540}$	0.98	0.0536	2.1384	3.0593	29
	$Y = 0.01376 (D^2H4)^{0.84861}$	.96	.0846	3.7728	6.7502	29
	$Y = 0.05675 (D^2)^{1.06593}(Mh)^{0.26495}$	.94	.0481	—	—	17
Wood in stem from stump to saw-log merchantable top						
	$Y = 0.08004 (D^2)^{1.01638}$	.70	.1086	2.3749	0.3935	17
	$Y = 0.00834 (D^2H4)^{0.82646}$	.75	.0990	4.1079	0.6390	17
	$Y = 0.01310 (D^2)^{0.73948}(Mh)^{1.04979}$	.95	.0443	—	—	17
Wood in stem from stump to 4-inch d.i.b. top						
	$Y = 0.02187 (D^2)^{1.33715}$	.98	.0711	2.1384	3.0593	29
	$Y = 0.00596 (D^2H4)^{0.90710}$	.99	.0440	3.7728	6.7502	29
	$Y = 0.08655 (D^2)^{0.92294}(Mh)^{0.28100}$	.95	.0390	—	—	17
Wood in crown (all branches and topwood < 4 inches d.i.b.)						
	$Y = 0.01373 (D^2)^{1.22278}$	.82	.1924	2.1384	3.0593	29
	$Y = 0.00702 (D^2H4)^{0.77299}$	.72	.2389	3.7728	6.7502	29
	$Y = 0.00105 (D^2)^{1.51487}(Mh)^{0.32265}$	.79	.1404	—	—	17

[a] $Y = a(D^2)^{b_1}$ or $Y = a(D^2H4)^{b_1}$ or $Y = a(D^2)^{b_1}(Mh)^{b_2}$

where:

Y = component volume in cubic feet,
D = d.b.h. in inches,
$H4$ = tree height to 4-inch d.i.b. top in feet,
Mh = saw-log merchantable height in feet,
a, b_1, b_2 = regression coefficients.

[b] Log_{10} form.

COMPUTATION OF CONFIDENCE LIMITS

Tables 6, 7, 8, and 9 contain the standard errors of the estimate, the sample mean of x, and the corrected sums of squares for x for each equation in Log_{10} form. These statistics can be used to calculate approximate confidence limits in pounds or cubic feet by using a modification of Cox's formula (Land 1972) for estimating confidence limits for lognormal means:

$$Y_{U,L} = 10^{\text{Log}\,Y \pm Z \sqrt{S^2_{y\cdot x}\left[\frac{1}{n} + \frac{(x-\bar{x})^2}{\Sigma(x-\bar{x})^2}\right] + \frac{S^4_{y\cdot x}}{2(n+1)}}} \qquad (8)$$

where:

$Y_{U,L}$ = upper and lower limits for Y,

Y = predicted weight or volume of component from equation (6),

Z = value from the standard normal table for appropriate confidence level,

$S_{y\cdot x}$ = standard error of estimate for prediction equation,

n = number of observations used to develop equation,

$\bar{x}$ = sample mean of log x — (from table of equations),

$\Sigma(x-\bar{x})^2$ = corrected sums of squares for log x — (from table of equations),

x = value of independent variable in $\log_{10}$ form.

Cox's method of approximation sufficiently estimates actual confidence limits when applied to samples with small variances, as occur in the total-tree and stem weight and volume southern red oak data sets. Thus, equation (8) should be used to approximate confidence limits for the single-variable equations presented in this Paper.

Table 10.—Predicted green weight of above-stump total-tree wood and bark for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
				Pounds			
				WOOD AND BARK[c]			
5	144	185	226	269	312		
6	216	277	340	403	468		
7	305	391	479	568	659		
8	410	526	644	765	887	1,011	
9	533	684	837	994	1,153	1,314	
10	674	864	1,058	1,256	1,458	1,662	1,868
11	833	1,068	1,308	1,553	1,802	2,054	2,310
12	1,011	1,296	1,588	1,885	2,187	2,493	2,803
13	1,209	1,549	1,897	2,252	2,613	2,979	3,349
14		1,827	2,238	2,656	3,081	3,513	3,950
15		2,130	2,609	3,097	3,593	4,096	4,605
16		2,459	3,012	3,575	4,147	4,728	5,316
17		2,814	3,446	4,091	4,746	5,411	6,084
18			3,914	4,646	5,390	6,145	6,909
19			4,414	5,240	6,079	6,930	7,792
20			4,948	5,873	6,814	7,768	8,734
21			5,515	6,547	7,595	8,659	9,735
22			6,117	7,261	8,423	9,603	10,797
				WOOD[d]			
5	116	149	182	216	251		
6	174	223	273	324	376		
7	245	314	385	457	531		
8	330	423	519	616	715	815	
9	429	550	674	801	929	1,059	
10	543	696	853	1,012	1,175	1,340	1,506
11	671	861	1,054	1,252	1,453	1,657	1,863
12	815	1,045	1,280	1,520	1,764	2,011	2,262
13	974	1,249	1,530	1,817	2,108	2,404	2,703
14		1,473	1,805	2,143	2,487	2,835	3,188
15		1,718	2,105	2,499	2,900	3,306	3,718
16		1,983	2,430	2,885	3,348	3,818	4,293
17		2,270	2,782	3,303	3,833	4,370	4,915
18			3,159	3,752	4,353	4,964	5,582
19			3,564	4,232	4,911	5,599	6,297
20			3,996	4,744	5,505	6,277	7,059
21			4,454	5,289	6,138	6,998	7,870
22			4,941	5,867	6,808	7,763	8,730

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.06632\,(D^2Th)^{1.11245}$.

[d] $Y = 0.05262\,(D^2Th)^{1.11420}$.

Table 11.—Predicted green weight of wood and bark in saw-log stem to 8-inch d.i.b. or saw-log merchantable top for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]					
	50	60	70	80	90	100
	Pounds					
	WOOD AND BARK[c]					
11	618	728	837	945	1,051	1,157
12	723	853	980	1,106	1,231	1,354
13	836	986	1,133	1,279	1,423	1,565
14	956	1,127	1,296	1,463	1,627	1,790
15	1,083	1,277	1,469	1,657	1,844	2,029
16	1,217	1,436	1,651	1,863	2,073	2,280
17	1,358	1,602	1,842	2,079	2,313	2,545
18	1,507	1,777	2,043	2,306	2,565	2,822
19	1,662	1,960	2,254	2,543	2,829	3,113
20	1,823	2,151	2,473	2,791	3,105	3,416
21	1,992	2,349	2,701	3,049	3,392	3,731
22	2,167	2,556	2,939	3,317	3,690	4,059
	WOOD[d]					
11	510	604	696	787	877	967
12	599	709	817	924	1,030	1,135
13	694	822	947	1,071	1,194	1,316
14	796	942	1,086	1,228	1,369	1,509
15	904	1,070	1,233	1,395	1,555	1,714
16	1,019	1,205	1,389	1,571	1,752	1,930
17	1,139	1,348	1,554	1,757	1,959	2,159
18	1,266	1,498	1,726	1,953	2,177	2,399
19	1,399	1,655	1,907	2,157	2,405	2,651
20	1,537	1,819	2,097	2,372	2,644	2,914
21	1,682	1,990	2,294	2,595	2,893	3,188
22	1,833	2,168	2,500	2,827	3,152	3,474

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.23227 (D^2Th)^{0.90557}$.

[d] $Y = 0.16578 (D^2Th)^{0.92239}$.

Table 12.—Predicted green weight of wood and bark in stem to 4-inch d.i.b. top for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
				Pounds			
				WOOD AND BARK[c]			
5	92	119	147	175	205		
6	140	181	224	267	312		
7	200	259	320	382	446		
8	272	353	436	521	608	697	
9	358	464	573	685	799	916	
10	457	592	731	874	1,020	1,169	1,321
11	570	738	912	1,090	1,272	1,458	1,648
12	697	903	1,115	1,333	1,556	1,784	2,016
13	839	1,087	1,343	1,605	1,874	2,148	2,427
14		1,290	1,594	1,906	2,225	2,550	2,881
15		1,514	1,870	2,236	2,610	2,992	3,381
16		1,759	2,172	2,597	3,032	3,475	3,926
17		2,024	2,500	2,989	3,489	3,999	4,518
18			2,854	3,412	3,983	4,565	5,158
19			3,235	3,868	4,515	5,175	5,847
20			3,643	4,356	5,085	5,828	6,585
21			4,079	4,877	5,693	6,526	7,373
22			4,544	5,432	6,341	7,269	8,212
				WOOD[d]			
5	74	96	119	143	167		
6	114	148	183	219	256		
7	163	212	262	314	367		
8	223	289	358	429	501	575	
9	294	381	471	564	660	757	
10	375	487	603	722	844	968	1,095
11	469	609	753	902	1,054	1,210	1,368
12	575	746	923	1,105	1,292	1,483	1,677
13	693	900	1,113	1,333	1,558	1,788	2,022
14		1,070	1,324	1,585	1,852	2,126	2,404
15		1,257	1,555	1,862	2,176	2,498	2,825
16		1,461	1,808	2,165	2,531	2,904	3,285
17		1,684	2,084	2,495	2,916	3,346	3,784
18			2,381	2,851	3,333	3,824	4,325
19			2,702	3,235	3,781	4,339	4,908
20			3,046	3,647	4,263	4,892	5,532
21			3,414	4,087	4,778	5,482	6,200
22			3,806	4,557	5,326	6,112	6,912

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.03062\,(D^2Th)^{1.15873}$.

[d] $Y = 0.02324\,(D^2Th)^{1.16832}$.

Table 13.—Predicted green weight of wood and bark in crown for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
	Pounds						
	WOOD AND BARK[c]						
5	44	56	68	81	93		
6	65	83	101	119	138		
7	91	116	141	166	192		
8	121	154	188	222	256	291	
9	156	199	242	286	330	374	
10	196	249	304	358	414	470	526
11	241	306	373	440	508	577	646
12	291	369	450	531	613	696	779
13	345	439	534	631	728	827	926
14		515	627	740	854	970	1,086
15		597	727	858	991	1,125	1,260
16		686	835	986	1,139	1,293	1,448
17		782	952	1,124	1,297	1,473	1,650
18			1,076	1,271	1,467	1,666	1,866
19			1,209	1,428	1,648	1,871	2,096
20			1,351	1,594	1,841	2,090	2,341
21			1,500	1,771	2,045	2,321	2,600
22			1,658	1,958	2,260	2,566	2,874
	WOOD[d]						
5	34	43	53	62	72		
6	51	64	78	91	105		
7	70	89	108	127	146		
8	93	118	143	168	193	219	
9	119	151	183	216	248	281	
10	149	189	229	269	310	352	393
11	182	231	280	330	380	430	481
12	219	278	337	396	457	517	578
13	260	329	399	470	541	613	685
14		385	467	549	633	717	801
15		445	540	636	732	829	927
16		510	619	729	839	951	1,063
17		580	704	829	954	1,081	1,209
18			794	935	1,077	1,220	1,364
19			891	1,049	1,208	1,368	1,530
20			993	1,169	1,346	1,525	1,705
21			1,101	1,296	1,493	1,691	1,891
22			1,215	1,430	1,647	1,866	2,086

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.02596 (D^2Th)^{1.07671}$.

[d] $Y = 0.02292 (D^2Th)^{1.05855}$.

Table 14.—Predicted volume of above-stump total-tree wood and bark for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
				Cubic feet			
				WOOD AND BARK[c]			
5	2.3	3.0	3.6	4.3	5.0		
6	3.5	4.5	5.4	6.4	7.5		
7	4.9	6.2	7.6	9.0	10.4		
8	6.5	8.4	10.2	12.1	14.0	15.9	
9	8.5	10.8	13.2	15.6	18.1	20.6	
10	10.7	13.6	16.6	19.7	22.8	25.9	29.1
11	13.1	16.8	20.5	24.3	28.1	31.9	35.8
12	15.9	20.3	24.8	29.3	34.0	38.6	43.4
13	19.0	24.2	29.5	35.0	40.5	46.0	51.7
14		28.5	34.7	41.1	47.6	54.1	60.8
15		33.1	40.4	47.8	55.4	63.0	70.7
16		38.1	46.5	55.1	63.8	72.5	81.4
17		43.5	53.1	62.9	72.8	82.8	92.9
18			60.2	71.3	82.5	93.9	105.3
19			67.8	80.2	92.9	105.6	118.6
20			75.8	89.8	103.9	118.2	132.6
21			84.4	99.9	115.6	131.5	147.6
22			93.4	110.6	128.0	145.6	163.4
				WOOD[d]			
5	1.8	2.3	2.9	3.4	3.9		
6	2.7	3.5	4.3	5.0	5.8		
7	3.8	4.9	6.0	7.1	8.2		
8	5.1	6.6	8.0	9.5	11.0	12.5	
9	6.7	8.5	10.4	12.3	14.3	16.2	
10	8.4	10.7	13.1	15.5	18.0	20.5	23.0
11	10.3	13.2	16.2	19.1	22.2	25.2	28.3
12	12.5	16.0	19.6	23.2	26.9	30.6	34.3
13	14.9	19.1	23.3	27.7	32.0	36.5	40.9
14		22.5	27.5	32.6	37.7	42.9	48.2
15		26.2	32.0	37.9	43.9	50.0	56.1
16		30.2	36.9	43.7	50.6	57.6	64.7
17		34.5	42.1	49.9	57.8	65.8	73.9
18			47.8	56.6	65.5	74.6	83.8
19			53.8	63.7	73.8	84.0	94.4
20			60.2	71.4	82.7	94.1	105.7
21			67.1	79.4	92.0	104.8	117.6
22			74.3	88.0	101.9	116.0	130.3

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.001220(D^2Th)^{1.09436}$.

[d] $Y = 0.000913\,(D^2Th)^{1.10025}$.

Table 15.—Predicted volume of wood and bark in stem to 8-inch d.i.b. or saw-log merchantable top for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]					
	50	60	70	80	90	100
	Cubic feet					
	WOOD AND BARK[c]					
11	9.6	11.3	13.0	14.6	16.3	17.8
12	11.2	13.2	15.2	17.1	19.0	20.8
13	13.0	15.2	17.5	19.7	21.9	24.0
14	14.8	17.4	20.0	22.5	25.0	27.4
15	16.7	19.7	22.6	25.4	28.2	31.0
16	18.8	22.1	25.3	28.5	31.7	34.8
17	20.9	24.6	28.2	31.8	35.3	38.8
18		27.2	31.2	35.2	39.1	42.9
19		30.0	34.4	38.7	43.0	47.3
20		32.9	37.7	42.5	47.2	51.8
21		35.8	41.1	46.3	51.4	56.5
22		38.9	44.7	50.3	55.9	61.4
	WOOD[d]					
11	7.8	9.2	10.6	12.0	13.3	14.7
12	9.1	10.8	12.4	14.0	15.6	17.2
13	10.6	12.5	14.4	16.2	18.1	19.9
14	12.1	14.3	16.5	18.6	20.7	22.8
15	13.7	16.2	18.7	21.1	23.5	25.8
16	15.4	18.2	21.0	23.7	26.4	29.0
17	17.2	20.4	23.4	26.5	29.5	32.4
18		22.6	26.0	29.4	32.7	36.0
19		24.9	28.7	32.4	36.1	39.7
20		27.4	31.5	35.6	39.6	43.6
21		29.9	34.4	38.9	43.3	47.6
22		32.6	37.5	42.3	47.1	51.9

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.004113\,(D^2Th)^{0.89093}$.

[d] $Y = 0.002805\,(D^2Th)^{0.91079}$.

Table 16.—Predicted volume of wood and bark in stem to 4-inch d.i.b. top for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
				Cubic feet			
				WOOD AND BARK[c]			
5	1.5	1.9	2.4	2.8	3.3		
6	2.3	2.9	3.6	4.3	5.0		
7	3.2	4.1	5.1	6.1	7.1		
8	4.4	5.6	6.9	8.2	9.6	11.0	
9	5.7	7.3	9.0	10.8	12.5	14.4	
10	7.2	9.3	11.5	13.7	16.0	18.2	20.6
11	9.0	11.6	14.3	17.0	19.8	22.7	25.6
12	11.0	14.1	17.4	20.8	24.2	27.7	31.2
13	13.2	17.0	20.9	24.9	29.0	33.2	37.4
14		20.1	24.8	29.5	34.4	39.3	44.3
15		23.5	29.0	34.5	40.2	46.0	51.9
16		27.3	33.6	40.0	46.6	53.3	60.1
17		31.3	38.5	45.9	53.5	61.2	69.0
18			43.9	52.3	60.9	69.7	78.6
19			49.7	59.2	68.9	78.8	88.9
20			55.8	66.5	77.5	88.6	99.9
21			62.4	74.4	86.6	99.0	111.7
22			69.4	82.7	96.3	110.1	124.2
				WOOD[d]			
5	1.2	1.5	1.9	2.2	2.6		
6	1.8	2.3	2.8	3.4	4.0		
7	2.5	3.3	4.0	4.8	5.6		
8	3.4	4.5	5.5	6.6	7.7	8.8	
9	4.5	5.9	7.2	8.7	10.1	11.6	
10	5.8	7.5	9.2	11.1	12.9	14.8	16.7
11	7.2	9.3	11.5	13.8	16.1	18.4	20.8
12	8.8	11.4	14.1	16.9	19.7	22.6	25.5
13	10.6	13.7	17.0	20.3	23.7	27.1	30.7
14		16.3	20.2	24.1	28.1	32.2	36.4
15		19.1	23.6	28.3	33.0	37.8	42.7
16		22.2	27.5	32.8	38.3	43.9	49.6
17		25.6	31.6	37.8	44.1	50.5	57.1
18			36.1	43.1	50.3	57.7	65.2
19			40.9	48.9	57.1	65.4	73.9
20			46.0	55.0	64.2	73.6	83.2
21			51.6	61.6	71.9	82.4	93.2
22			57.4	68.6	80.1	91.8	103.7

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.000567(D^2Th)^{1.13994}$.

[d] $Y = 0.000389\,(D^2Th)^{1.15821}$.

Table 17.—Predicted volume of wood and bark in crown for southern red oak trees[a]

D.b.h. (inches)	Total height (feet)[b]						
	40	50	60	70	80	90	100
	Cubic feet						
	WOOD AND BARK[c]						
5	0.7	0.9	1.1	1.3	1.5		
6	1.1	1.3	1.6	1.9	2.2		
7	1.5	1.8	2.2	2.6	3.0		
8	1.9	2.5	3.0	3.5	4.0	4.6	
9	2.5	3.1	3.8	4.5	5.2	5.9	
10	3.1	3.9	4.8	5.6	6.5	7.4	8.2
11	3.8	4.8	5.9	6.9	7.9	9.0	10.1
12	4.6	5.8	7.0	8.3	9.6	10.8	12.1
13	5.4	6.9	8.3	9.8	11.3	12.8	14.4
14		8.0	9.8	11.5	13.3	15.0	16.8
15		9.3	11.3	13.3	15.4	17.4	19.5
16		10.7	13.0	15.3	17.6	20.0	22.3
17		12.2	14.8	17.4	20.0	22.7	25.4
18			16.7	19.6	22.6	25.6	28.7
19			18.7	22.0	25.4	28.7	32.1
20			20.8	24.5	28.3	32.1	35.8
21			23.1	27.2	31.4	35.5	39.8
22			25.5	30.0	34.6	39.2	43.9
	WOOD[d]						
5	0.5	0.7	0.8	1.0	1.1		
6	.8	1.0	1.2	1.4	1.6		
7	1.1	1.4	1.7	2.0	2.3		
8	1.5	1.8	2.2	2.6	3.0	3.4	
9	1.9	2.3	2.8	3.3	3.8	4.3	
10	2.3	2.9	3.5	4.1	4.7	5.4	6.0
11	2.8	3.5	4.3	5.0	5.8	6.5	7.3
12	3.4	4.3	5.1	6.0	6.9	7.8	8.7
13	4.0	5.0	6.1	7.1	8.2	9.3	10.3
14		5.9	7.1	8.3	9.6	10.8	12.1
15		6.8	8.2	9.6	11.0	12.5	13.9
16		7.7	9.4	11.0	12.6	14.3	15.9
17		8.8	10.6	12.5	14.3	16.2	18.0
18			11.9	14.0	16.1	18.2	20.3
19			13.4	15.7	18.0	20.4	22.7
20			14.9	17.5	20.1	22.7	25.3
21			16.5	19.3	22.2	25.1	28.0
22			18.1	21.3	24.5	27.6	30.8

[a] Blocked-in area indicates range of data.

[b] Includes 1-foot stump allowance.

[c] $Y = 0.000465\,(D^2Th)^{1.06191}$.

[d] $Y = 0.000415\,(D^2Th)^{1.03977}$.

U.S. Government Printing Office: 1980- 635-100/4007 Region No. 3-11

Clark, Alexander, III, Douglas R. Phillips, and Harry C. Hitchcock III.
1980. Predicted weights and volumes of southern red oak trees on the Highland Rim in Tennessee. USDA For. Serv., Res. Pap. SE-208, 23p. Southeast. For. Exp. Stn., Asheville, N.C.

Equations are presented for predicting green and dry weight and green volume of the total tree above stump and its components using d.b.h. and total height, d.b.h. and height to a 4-inch top, d.b.h. and saw-log merchantable height, and d.b.h. alone. Tables developed from equations show weight and volume of the total tree and its components by d.b.h. and total height class.

KEYWORDS: *Quercus falcata* Michx., biomass, component proportions, equations, specific gravity, moisture content, weight per cubic foot.

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KEYWORDS: *Quercus falcata* Michx., biomass, component proportions, equations, specific gravity, moisture content, weight per cubic foot.

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Research Paper
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Predicted Weights and Volumes of Northern Red Oak Trees in Western North Carolina

by Alexander Clark III, Douglas R. Phillips,
and James G. Schroeder

GOVT. DOCUMENTS
DEPOSITORY ITEM
DEC 23 1980

Conversion factors: English to metric

Multiply	*by*	*To obtain*
Inches	2.540	centimeters
Feet	.3048	meters
Pounds	.4536	kilograms
Cubic feet	.02832	cubic meters
Pounds per cubic feet	16.02	kilograms per cubic meter

All English units of measure in this report can be converted to metric units by multiplying by the appropriate conversion factor listed above.

July 1980
Southeastern Forest Experiment Station
Asheville, North Carolina

Predicted Weights and Volumes of Northern Red Oak Trees in Western North Carolina[1]

by

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ABSTRACT.—Total weights and volumes, above stump, were determined for 71 northern red oak (*Quercus rubra* L.) trees 6 to 24 inches d.b.h. growing in fully stocked oak-hickory stands in western North Carolina. Equations are presented for predicting green and dry weights and green volume of the total tree, above stump, and its components using d.b.h. and total height, d.b.h. and height to a 4-inch top, d.b.h. and saw-log merchantable height, and d.b.h. alone. Tables developed from equations show weight and volume of the total tree and its components by d.b.h. and total height classes. Seventy-five percent of total-tree weight was in stem to a 4-inch top and 25 percent in crown. The average tree had 85 percent of its green weight in wood and 15 percent in bark. Total-tree wood had an average specific gravity of 0.581, an average moisture content of 80 percent, and an average green weight per cubic foot of 65 pounds. The average weight of wood and bark per cubic foot of wood for the total tree was 77 pounds.

Keywords: *Quercus rubra* L., biomass, component proportions, equations, specific gravity, moisture content, weight per cubic foot.

Increasing demands for wood, escalating costs, and the energy shortage have forced forest industries in the South to consider utilizing all parts of trees. Utilizing the total tree above the stump compared to utilizing only the merchantable stem can increase yields from individual hardwood trees by as much as 65 percent (Clark 1978). Equations for estimating total-tree weight and volume are needed to evaluate and utilize total trees.

This Paper presents green volumes and green and dry weights of above-stump biomass of commercial-size northern red oaks (*Quercus rubra* L.) growing in uneven-aged stands in the mountains of western North Carolina. Equations and yield tables predict weight and volume of the total tree and its components (wood, bark, saw logs, stem, and crown). Wood and bark specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components.

PROCEDURES

Field

A total of 71 northern red oak trees were selected from two fully stocked, uneven-aged oak-hickory stands to determine winter biomass. A stratified random sample of 36 pulpwood-size trees (trees 5.6 to 11.5 inches d.b.h.) was selected from a stand in Haywood County on the French Broad District of the Pisgah National Forest. The dominant and codominant trees in the stand were 10 to 14 inches d.b.h., and the stand had an average site index for northern red oak of 80. Five to seven trees were selected from each 1-inch d.b.h. class from 6 to 11 inches d.b.h. The trees sampled ranged from 41 to 55 years old and averaged 49 years.

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[1] This study was conducted in cooperation with the Range, Timber, and Wildlife Program Area of Region 8 of the National Forest System. Field personnel were provided by the Pisgah and French Broad Ranger Districts of the Pisgah National Forest.

A second stratified random sample of 35 dominant and codominant sawtimber-size trees ($\geq$ 11.6 inches d.b.h.) was selected from a mature stand in Buncombe County on the Pisgah District of the Pisgah National Forest. The stand had an average site index of 90. Three to six trees from each 2-inch d.b.h. class were sampled. Form class of the sawtimber trees ranged from 71 to 86 and averaged 79. The trees ranged from 53 to 114 years old and averaged 76 years. Means and ranges in dimensions of sample trees are shown in table 1.

Trees were felled and limbed during the winter, and the main stem of each tree was bucked into merchantable saw logs and pulpwood. Saw logs 8 to 16 feet long were cut from the main stem to an 8-inch d.i.b. top or to a degrading quality indicator such as large knots. Stem d.i.b. at the saw-log top averaged 9.9 inches (table 1). All material between the saw-log merchantable top and the 4-inch d.i.b. top was classed as "pulpwood." All trees had a discernible main stem to a 4-inch top. In pulpwood trees, stem material between the 4-and 2-inch d.i.b. tops was classed as "topwood." The crown of sawtimber-size trees was cut up and weighed in two categories: (1) branches $\geq$ 4.0 inches d.o.b., and (2) branches $<$ 4.0 inches d.o.b. Pulpwood crowns were divided into branches $\geq$ 2.0 inches and branches $<$ 2.0 inches d.o.b. The tip of the stem (2 inches d.i.b. to top) was included as branch material in the study. All crown and pulpwood material was weighed to the nearest one-quarter pound. Saw logs were weighed individually to the nearest pound.

From each sawtimber tree, disks were removed at the butt, at each saw-log bucking point, at the points where d.i.b. measured 8, 6, and 4 inches, and from branches randomly selected from each branch-size category. In pulpwood-size trees, disks were cut at the butt, at quarter points to a 4-inch top, and at a 2-inch top. Each disk was sealed in a polyethylene bag for subsequent determinations of moisture content, specific gravity, and bark percent.

Laboratory

Specific gravity was computed on a green-volume and ovendry-weight basis. Moisture con-

Table 1.—Means and ranges in dimensions of northern red oak trees sampled on the Pisgah National Forest in western North Carolina

D.b.h. class (inches)	Sample trees	D.b.h.		Total height		Height to 4-inch d.i.b. top		Height to saw-log merchantable top[1]		D.i.b. at saw-log merchantable top	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
	Number	..... *Inches*		.... *Feet*		....		....		..... *Inches*	
6	5	6.1	5.9– 6.4	61	56– 64	28	18–33	—	—	—	—
7	7	7.1	6.6– 7.5	66	53– 72	39	33–43	—	—	—	—
8	7	8.1	7.6– 8.5	69	66– 74	42	36–48	—	—	—	—
9	5	9.0	8.7– 9.4	75	74– 77	48	43–51	—	—	—	—
10	6	10.1	9.6–10.5	76	65– 82	52	44–65	—	—	—	—
11	6	11.0	10.6–11.3	80	72– 86	58	55–60	—	—	—	—
12	5	12.2	11.7–12.9	83	67–104	60	50–79	33	25–37	9.1	8.2– 9.8
14	5	14.3	13.9–14.9	94	91– 98	70	65–75	47	35–64	8.3	7.4– 9.9
16	6	15.6	15.0–16.1	96	82–107	73	61–84	48	37–65	9.4	8.2–11.8
18	6	17.7	17.0–18.5	98	89–103	77	70–84	54	43–62	10.0	7.6–12.6
20	5	20.1	19.0–20.9	102	96–106	79	72–87	53	45–62	10.8	9.4–12.5
22	5	22.0	21.3–22.7	106	98–118	88	82–93	62	50–78	9.3	7.8–13.1
24	3	24.0	23.6–24.7	102	91–116	84	76–98	53	50–60	14.7	14.3–15.0
All classes	71	13.0	5.9–24.7	84	53–118	60	18–98	50	25–78	9.9	7.4–15.0

[1] Height to 8-inch d.i.b. or saw-log merchantable top.

tent was computed on an ovendry-weight basis after samples were dried to a constant weight at 103° C. Percentage of bark was determined from disks on a green-weight basis. Moisture content, specific gravity, and percentage of bark in stem, branches, and total tree were calculated by weighting disk values in proportion to the volume of the component they represented. Weighted values for moisture content were used to convert component green weights to ovendry weights.

Green weights per cubic foot of wood and bark were calculated from weighted values for specific gravity and moisture content with the equation:

Green weight per cubic foot

$$= \left[1 + \frac{\text{M.C.}}{100}\right] \times (\text{S.G.}) \times (\text{C}) \qquad (1)$$

where:

M.C. = weighted moisture content in percent,
S.G. = weighted specific gravity,
C = 62.4 pounds (weight of water per cubic foot).

Cubic-foot volume of green wood and bark were computed by dividing component weight by its green weight per cubic foot. Total green cubic-foot volume (wood and bark combined) was computed by adding the green volume of bark to the green volume of wood.

Analysis

Linear regression equations were developed to predict green and dry weights and green volumes of wood and bark in the total tree and its components. Independent variables were: diameter at breast height (D), total height (Th), sawlog merchantable height (Mh), and height to a 4-inch top (H4), both separately and in various combinations.

Grouping the data into D²Th classes and plotting the variance of Y over D² and D²Th indicated that the variances of predicted weights and volumes increased with increasing D² and D²Th. A logarithmic transformation (to the base 10) was used to obtain a relatively homogeneous variance, which is assumed in regression analysis. Thus, regression equations for tree and component weights and volumes were calculated using the equations:

$$\log Y = b_0 + b_1 \log X + \epsilon \qquad (2)$$

$$\log Y = b_0 + b_1 \log X_1 + b_2 \log X_2 + \epsilon \qquad (3)$$

where:

Y = predicted weight or volume of component
X = D^2, D^2Th, D^2H4, or D^2Mh,
X_1 = D^2,
X_2 = Th, H4, or Mh
ϵ = sampling error,
b_i = regression coefficients.

When logarithmic estimates are converted back to original units, they are biased downward because the antilogarithm of an estimated mean gives the geometric rather than the arithmetic mean (Cunia 1964). To account for this bias, a correction factor was computed using a procedure described by Baskerville (1972) and applied to each equation. The equation forms, including the correction factor, are:

$$Y = 10^{b_0 + b_1 \log X + \frac{S^2_{y \cdot x}}{2}} \qquad (4)$$

and

$$Y = 10^{b_0 + b_1 \log X_1 + b_2 \log X_2 + \frac{S^2_{y \cdot x}}{2}} \qquad (5)$$

where:

$S^2_{y \cdot x}$ = error mean square from regression analysis

Equations (4) and (5) can be simplified to:

$$Y = aX^{b_1} \qquad (6)$$

and

$$Y = aX_1^{b_1}X_2^{b_2} \qquad (7)$$

where:

$$a = 10^{b_0 + \frac{S^2_{y \cdot x}}{2}}$$

Separate prediction equations were developed for the pulpwood and sawtimber trees. Statistical tests (Snedecor and Cochran 1967) indicated no significant differences in the slopes or intercepts of these equations at the 0.01 probability level for the total tree and stem weights or volumes. Therefore, the pulpwood and sawtimber trees were combined, and one series of equations was developed for trees 6 to 24 inches d.b.h.

SAMPLE TREE CHARACTERISTICS

Total Tree

Green weight of the trees sampled ranged from an average of 457 pounds for 6-inch trees to 12,535 pounds for 24-inch trees. Assuming the trees were composed solely of wood, bark, and water, 44 percent of their green weight was water; 47 percent was wood; and 9 percent was bark. The proportions of total-tree weight in wood and bark did not vary with tree size. The proportion of tree weight in bark ranged from 14 to 17 percent and averaged 15 percent on a green basis. On a dry basis, bark made up an average of 17 percent of total-tree weight.

The proportion of tree weight in crown material (all live branches and stem < 4-inch d.i.b.) ranged from 19 to 29 percent on a green basis but did not vary consistently with tree size. The proportion of tree green weight in crown averaged 25 percent, and the proportion in the stem to a 4-inch top averaged 75 percent.

The green and dry weights of all wood and bark and the distribution of wood and bark throughout the tree are presented in tables 2 and 3 for pulpwood trees and in tables 4 and 5 for sawtimber trees. On the average, pulpwood trees had 79 percent of their total green wood weight in the stem to a 4-inch d.i.b. top and 21 percent in the crown (topwood and branches). Sawtimber trees on the average had 77 percent of their green wood weight in the stem to a 4-inch top and 23 percent in crown. Sixty-six percent of their green wood weight was in saw-log material and 11 percent in pulpwood. Wood and bark were not distributed evenly throughout the tree; the stem to a 4-inch top of the average sawtimber tree contained 77 percent of all the green wood in the tree but only 61 percent of the bark. Sawtimber tree crowns contained 23 percent of the green wood and 39 percent of the bark.

Stem Components

The proportion of stem weight to a 4-inch top in wood increased and the proportion in bark decreased as stem d.b.h. increased. The proportion of stem weight in wood increased from 85 percent

Table 2.—Average green and dry weights of wood in the total tree and distribution of wood in main stem and branches in northern red oak pulpwood trees

D.b.h. class (inches)	Average total height	Sample trees	Total-tree wood weight	Proportion of wood in —					
				Main stem			Branches (inches d.o.b.)		
				Pulpwood[1]	Topwood[2]	Total stem[3]	≥ 2 inches	< 2 inches	All branches
	Feet	*Number*	*Pounds*	...... *Percent*					
				GREEN					
6	61	5	381	73	11	84	4	12	16
7	66	7	547	77	9	86	3	11	14
8	69	7	766	78	6	84	6	10	16
9	75	5	999	77	5	82	8	10	18
10	76	6	1,288	79	3	82	8	10	18
11	80	6	1,566	83	2	85	6	9	15
Average	—	—	923	79	5	84	6	10	16
				DRY					
6	61	5	215	72	12	84	3	13	16
7	66	7	311	76	9	85	3	12	15
8	69	7	426	76	7	83	6	11	17
9	75	5	560	76	6	82	7	11	18
10	76	6	718	78	3	81	8	11	19
11	80	6	868	81	3	84	6	10	16
Average	—	—	517	78	5	83	6	11	17

[1] Pulpwood in stem from butt to 4-inch d.i.b. top.

[2] Stem material from 4-inch to 2-inch d.i.b. top.

[3] Main stem to 2-inch d.i.b. top.

Table 3.—Average green and dry weights of bark in the total tree and distribution of bark in main stem and branches in northern red oak pulpwood trees

D.b.h. class (inches)	Average total height	Sample trees	Total-tree bark weight	Proportion of bark in —					
				Main stem			Branches (inches d.o.b.)		
				Pulpwood[1]	Topwood[2]	Total stem[3]	> 2 inches	< 2 inches	All crown
	Feet	*Number*	*Pounds*	.... *Percent*					
				GREEN					
6	61	5	76	60	13	73	5	22	27
7	66	7	104	65	10	75	4	21	25
8	69	7	146	66	7	73	7	20	28
9	75	5	185	65	5	70	10	20	30
10	76	6	229	67	2	69	10	21	31
11	80	6	266	70	2	72	8	20	28
Average	—	—	167	66	6	72	8	20	28
				DRY					
6	61	5	46	60	13	74	5	21	26
7	66	7	63	65	10	75	4	21	25
8	69	7	90	67	7	74	8	18	26
9	75	5	109	66	5	71	10	19	29
10	76	6	139	67	3	70	10	20	30
11	80	6	160	71	2	73	8	19	27
Average	—	—	101	67	6	73	8	19	27

[1] Pulpwood in stem from butt to 4-inch d.i.b. top.

[2] Stem material from 4-inch to 2-inch d.i.b. top.

[3] Main stem to 2-inch d.i.b. top.

Table 4.—Average green and dry weights of wood in the total tree and distribution of wood in main stem and branches in northern red oak sawtimber trees

D.b.h. class (inches)	Average total height	Sample trees	Total-tree wood weight	Proportion of wood in —					
				Main stem			Branches (inches d.o.b.)		
				Saw-log[1]	Pulpwood[2]	Total stem[3]	≥ 4 inches	< 4 inches	All branches
	Feet	*Number*	*Pounds*	.... *Percent*					
				GREEN					
12	83	5	2,139	56	23	79	4	17	21
14	94	5	3,346	65	12	77	9	14	23
16	96	6	3,957	65	13	78	10	12	22
18	98	6	5,169	69	10	79	11	10	21
20	102	5	6,389	70	9	79	11	10	21
22	106	5	9,186	67	7	74	16	10	26
24	102	5	10,631	63	10	73	16	11	27
Average	—	—	5,484	66	11	77	12	11	23
				DRY					
12	83	5	1,196	55	23	78	4	18	22
14	94	5	1,847	63	12	75	10	15	25
16	96	6	2,227	64	13	77	10	13	23
18	98	6	2,847	68	9	77	12	11	23
20	102	5	3,467	68	8	78	11	11	22
22	106	5	5,109	65	7	72	17	11	28
24	102	5	5,792	62	10	72	16	12	28
Average	—	—	3,026	65	10	75	13	12	25

[1] Saw log to 8-inch d.i.b. or saw-log merchantable top.

[2] Pulpwood in stem from saw-log top to 4-inch d.i.b. top.

[3] Main stem to 4-inch d.i.b. top.

Table 5.—Average green and dry weights of bark in the total tree and distribution of bark in main stem and branches in northern red oak sawtimber trees

D.b.h. class (inches)	Average total height	Sample trees	Total-tree bark weight	Proportion of bark in —					
				Main stem			Branches (inches d.o.b.)		
				Saw-log[1]	Pulpwood[2]	Total stem[3]	≥ 4 inches	< 4 inches	All crown
	Feet	*Number*	*Pounds*	*Percent*					
				GREEN					
12	83	5	402	45	19	64	5	31	36
14	94	5	586	51	11	62	10	28	38
16	96	6	656	51	12	63	13	24	37
18	98	6	841	55	9	64	14	22	36
20	102	5	1,047	56	8	64	15	21	36
22	106	5	1,719	52	6	58	21	21	42
24	102	5	1,904	47	9	56	21	23	44
Average	—	—	956	52	9	61	16	23	39
				DRY					
12	83	5	244	46	21	67	5	28	33
14	94	5	369	51	11	67	11	27	38
16	96	6	406	51	12	63	13	24	37
18	98	6	526	55	9	64	14	22	36
20	102	5	646	56	9	65	15	20	35
22	106	5	1,112	52	6	58	21	21	42
24	102	5	1,240	49	8	57	22	21	43
Average	—	—	605	52	9	61	17	22	39

[1] Saw log to 8-inch d.i.b. or saw-log merchantable top.

[2] Pulpwood in stem from saw-log top to 4-inch d.i.b. top.

[3] Main stem to 4-inch d.i.b. top.

in 6-inch trees to 88 percent in 24-inch trees, while the proportion in bark decreased from 15 percent in 6-inch trees to 12 percent in 24-inch trees. On the average, 88 percent of the stem green weight was wood and 12 percent was bark.

Crown Components

When the crown was analyzed separately, the proportion of its green weight in wood averaged 77 percent and the proportion in bark averaged 23 percent on a green basis. Comparable figures on a dry basis were 78 and 24 percent, respectively.

On the average, 6 percent of the weight of wood in pulpwood trees was in topwood, 5 percent in branches ≥ 2.0 inches d.o.b., and 10 percent was in branches < 2.0 inches d.o.b. (table 2). The average sawtimber tree had 12 percent of its wood in crown material ≥ 4.0 inches d.o.b. and 11 percent in branches < 4.0 inches d.o.b. (table 4).

Physical Properties

Wood and bark specific gravity, moisture content, and green weight per cubic foot for the total tree and its components are presented in table 6. Wood specific gravity and moisture content did not vary significantly with tree size. Wood specific gravity averaged 0.581 for the total tree and 0.574 for the stem—slightly higher than the 0.56 reported by the Forest Products Laboratory (1974) for northern red oak stem wood. Pulpwood had the highest wood specific gravity, averaging 0.608, and saw-log wood the lowest, averaging 0.568. Wood moisture content ranged from 69 percent in the branches to 85 percent in saw logs and averaged 80 percent for the total tree. Green weight of wood per cubic foot averaged 65 pounds in the main stem and total tree.

Specific gravity of bark was lowest in branches (0.589) and highest in the pulpwood sec-

Table 6.—Average wood and bark specific gravity, moisture content, and green weight per cubic foot for northern red oak trees and tree components

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	*Pounds*
	WOOD		
Total tree	0.581 ± 0.020	80 ± 4.9	65 ± 1.5
Stem (butt to 4-inch d.i.b. top)	.574 ± .021	83 ± 5.4	65 ± 1.7
Saw log (butt to 8-inch d.i.b. top)	.568 ± .022	85 ± 5.8	66 ± 1.5
Pulpwood (8- to 4-inch d.i.b. top)	.608 ± .026	72 ± 4.7	65 ± 1.9
Branches	.605 ± .024	69 ± 4.0	64 ± 1.9
	BARK		
Total tree	0.616 ± .028	63 ± 5.8	62 ± 2.0
Stem (butt to 4-inch d.i.b. top)	.631 ± .032	61 ± 6.1	63 ± 2.3
Saw log (butt to 8-inch d.i.b. top)	.634 ± .038	58 ± 6.0	63 ± 2.5
Pulpwood (8- to 4-inch d.i.b. top)	.658 ± .038	55 ± 4.8	64 ± 2.2
Branches	.589 ± .046	66 ± 9.0	61 ± 2.6

tion of the main stem (0.658). Total-tree bark specific gravity was higher than wood specific gravity and averaged 0.616. Bark moisture content averaged 63 percent for the total tree, lower than the corresponding value for wood. Bark moisture content was the highest in branches (66 percent) and lowest in pulpwood (55 percent). Green bark weight per cubic foot ranged from 61 pounds in branches to 64 pounds in pulpwood and averaged 62 pounds in the total tree.

The weight of wood and bark per unit volume of wood is a useful factor for estimating the volume of wood in a tree or its components when weight of wood and bark is known. The average green weight of wood and bark per cubic foot of wood was 77 pounds for the total tree and 75 pounds for the stem (table 7). Branch green weight of wood and bark per cubic foot of wood averaged 83 pounds.

Green weight per cubic foot of wood and bark combined averaged 65 pounds for the total tree and the stem and 63 pounds for branches (table 7).

PREDICTION EQUATIONS

A series of equations was developed to predict weights and volumes of total trees and their components. Since tree height is measured to different top limits by various organizations, equations were developed using D^2 alone and in combination with Th, H4, and Mh as independent variables. When Th and H4 were used with D^2, the one-variable equation (2) and two-variable equation (3) predicted total-tree and component weights and volumes equally well. The use of height as a separate variable did not improve the coefficient of determination or reduce the standard error. Thus, the single variable equation was used to predict tree weight and volume when using D^2, D^2Th, and D^2H4 as the independent variable. When D^2 and Mh were used as separate variables in equation (3), the coefficient of determination (R^2) increased 15 to 20 percent and the standard error was reduced. Thus, the two-variable equation was used when D^2 and Mh were the independent variables.

All independent variable combinations were good predictors of weights and volumes, but equations using D^2Th were the best predictors of total-tree weights and volumes. Equations using D^2 + Mh were the best estimators of saw-log merchantable stem weight and volume, while equations using D^2H4 were the best predictors of stem weight and volume to a 4-inch top. When average tree heights and stem taper are similar to those of our sample trees, the equations using d.b.h. alone will result in good estimates of tree weight and volume. However, when average tree heights by d.b.h. classes are different, the equations that include a height variable should be ap-

Table 7.—Average green weight of wood and bark per cubic foot of wood and average weight of wood and bark per cubic foot of wood and bark for northern red oak trees and tree components

Tree component	Average and standard deviation	
	Green weight of wood and bark per cubic foot of wood	Green weight of wood and bark per cubic foot of wood and bark
	Pounds	
Total tree	77 ± 1.9	65 ± 1.4
Stem (butt to 4-in. d.i.b. top)	75 ± 1.9	65 ± 1.5
Saw log (butt to 8-in. d.i.b. top)	75 ± 1.8	65 ± 1.5
Pulpwood (8- to 4-in. d.i.b. top)	78 ± 3.2	65 ± 1.6
Branches	83 ± 3.2	63 ± 1.7

plied directly or used to develop local weight-volume tables based on d.b.h. alone.

Appendix tables 8 and 9 present equations for predicting all weights and volumes measured for total trees and all their components using D^2Th. Appendix tables 10 and 11 present equations that use D^2, D^2H4, and $D^2 + Mh$ to predict the green weights of wood and bark and volume of wood for the most important tree components. The Appendix also describes a method for placing confidence limits about predictions made with the equations.

A complete list of equations based on D^2, D^2H4, and D^2Mh for predicting the green and dry weights and volume of wood and bark of all tree components listed in tables 8 and 9 is available from the authors at the Southeastern Forest Experiment Station, Forestry Sciences Laboratory, Athens, Georgia 30602. Also available are uncorrected sums, sums of squares, and their cross products for the independent and dependent variables listed in tables 8 and 9. These data make it possible to statistically compare and combine equations. They also allow for the addition of observations and for computation of error terms.

BIOMASS TABLES

Equations based on D^2Th from tables 8 and 9 were used to develop tables of biomass weight and volume. Tables 12–15 show predicted green weights of wood and bark and wood alone in the total tree, the saw-log stem to an 8-inch d.i.b. or saw-log merchantable top, the stem to a 4-inch d.i.b. top, and the crown. Tables 16–19 show predicted green volumes of wood and bark and wood alone in the total tree and its components. The predicted weight or volume of bark in a tree or component can be estimated by subtracting the value in the table for wood alone from the corresponding value in the table for wood and bark combined.

Similar-size trees may vary in weight and volume because of differences in crown size, stem taper, and weight per cubic foot. Therefore the equations and tables should be applied only to trees growing in natural, fully stocked stands which have stem taper rates and weights per cubic foot similar to the trees sampled.

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Appendix

COMPUTATION OF CONFIDENCE LIMITS

Tables 8, 9, 10, and 11 contain the standard errors of the estimate, the sample mean of x, and the corrected sums of squares for x for each equation in $\log_{10}$ form. These statistics can be used to calculate approximate confidence limits in pounds or cubic feet using a modification of Cox's formula (Land 1972) for estimating confidence limits for lognormal means:

$$Y_{U,L} = 10^{\log Y \pm Z \sqrt{S^2_{y\cdot x}\left[\frac{1}{n} + \frac{(x-\bar{x})^2}{\Sigma(x-\bar{x})^2}\right] + \frac{S^4_{y\cdot x}}{2(n+1)}}} \tag{8}$$

where:

$Y_{U,L}$ = upper and lower limits for Y,
Y = predicted weight or volume of component from equation (6),
Z = value from the standard normal table for appropriate confidence level,
$S_{y\cdot x}$ = standard error of estimate for prediction equation,
n = number of observations used to develop equation,
$\bar{x}$ = sample mean of log x — (from table of equations),
$\Sigma(x-\bar{x})^2$ = corrected sums of squares for log x — (from table of equations),
x = value of independent variable in $\log_{10}$ form.

Cox's method of approximation sufficiently estimates actual confidence limits when applied to samples with small variances as occur in the total tree and stem weight and volume of northern red oak data sets. Thus, equation (8) should be used to approximate confidence limits for the single-variable equations presented in this Paper.

Table 8.—Regression equations for estimating above-stump green and dry weights of the total tree and its components for northern red oak trees 6 to 24 inches d.b.h., using d.b.h. and total height as independent variables

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] $(S_{y \cdot x})$[c]	Number trees sampled (N)
Total tree (excluding foliage):				
Green weight	$Y = 0.18579 (D^2Th)^{1.00655}$	0.99	0.0396	71
Dry weight	$Y = 0.10987 (D^2Th)^{1.00179}$	.99	.0441	71
All wood in tree:				
Green weight	$Y = 0.14803 (D^2Th)^{1.01315}$	.99	.0396	71
Dry weight	$Y = 0.08959 (D^2Th)^{1.00423}$	.99	.0442	71
All bark in tree:				
Green weight	$Y = 0.03980 (D^2Th)^{0.96995}$	.98	.0558	71
Dry weight	$Y = 0.02040 (D^2Th)^{0.98937}$	.98	.0606	71
Wood and bark in stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.05116 (D^2Th)^{1.08771}$	.95	.0546	35
Dry weight	$Y = 0.02929 (D^2Th)^{1.08388}$	.95	.0590	35
Wood in stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.04433 (D^2Th)^{1.08928}$	.95	.0554	35
Dry weight	$Y = 0.02605 (D^2Th)^{1.08093}$	.94	.0602	35
Bark in stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.00653 (D^2Th)^{1.08088}$	.92	.0705	35
Dry weight	$Y = 0.00319 (D^2Th)^{1.10598}$	.92	.0716	35
Wood and bark in stem from stump to 8-inch d.i.b. top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.06016 (D^2Th)^{1.08101}$	.97	.0445	35
Dry weight	$Y = 0.03445 (D^2Th)^{1.07718}$	.96	.0496	35
Wood in stem from stump to 8-inch d.i.b top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.05212 (D^2Th)^{1.08258}$	.97	.0448	35
Dry weight	$Y = 0.03063 (D^2Th)^{1.07422}$	.96	.0502	35
Bark in stem from stump to 8-inch d.i.b. top (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.00769 (D^2Th)^{1.07418}$	.93	.0673	35
Dry weight	$Y = 0.00376 (D^2Th)^{1.09928}$	.93	.0683	35
Wood and bark in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.13729 (D^2Th)^{1.00877}$	.99	.0356	71
Dry weight	$Y = 0.08222 (D^2Th)^{1.00092}$	.99	.0388	71
Wood in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.11034 (D^2Th)^{1.01741}$	.99	.0370	71
Dry weight	$Y = 0.06691 (D^2Th)^{1.00637}$	.99	.0404	71
Bark in stem from stump to 4-inch d.i.b. top:				
Green weight	$Y = 0.03040 (D^2Th)^{0.95031}$	.98	.0519	71
Dry weight	$Y = 0.01591 (D^2Th)^{0.96871}$	.98	.0548	71

Continued

Table 8.—Regression equations for estimating above-stump green and dry weights of the total tree and its components for northern red oak trees 6 to 24 inches d.b.h., using d.b.h. and total height as independent variables—Continued

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)[c]	Number trees sampled (N)
Wood and bark in crown (all branches and topwood < 4-inch d.i.b.):				
Green weight	$Y = 0.05004 (D^2Th)^{0.99476}$	.92	.1249	71
Dry weight	$Y = 0.02858 (D^2Th)^{0.99901}$	.92	.1259	71
Wood in crown (all branches and topwood < 4 inches d.i.b.):				
Green weight	$Y = 0.03901 (D^2Th)^{0.99387}$	.92	.1290	71
Dry weight	$Y = 0.02337 (D^2Th)^{0.99256}$	.92	.1277	71
Bark in crown (all branches and topwood < 4 inches d.i.b.):				
Green weight	$Y = 0.01107 (D^2Th)^{0.99723}$	.93	.1186	71
Dry weight	$Y = 0.00542 (D^2Th)^{1.01942}$	.93	.1235	71
Wood and bark in crown ≥ 4.0 inches d.o.b. (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.0000010 (D^2Th)^{1.96022}$	.77	.2418	35
Dry weight	$Y = 0.0000007 (D^2Th)^{1.94752}$	.77	.2420	35
Wood in crown ≥ 4.0 inches d.o.b. (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.00000086 (D^2Th)^{1.95391}$	.76	.2475	35
Dry weight	$Y = 0.00000066 (D^2Th)^{1.92791}$	.77	.2468	35
Bark in crown ≥ 4.0 inches d.o.b. (trees ≥ 11.0 inches d.b.h.):				
Green weight	$Y = 0.00000014 (D^2Th)^{1.98740}$	.80	.2228	35
Dry weight	$Y = 0.00000006 (D^2Th)^{2.02410}$	.80	.2288	35

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[a] $Y = b_0 (D^2Th)^{b_1}$

where

Y = component weight in pounds,

D = d.b.h. in inches,

Th = total height of tree in feet,

b_0, b_1 = regression coefficients

[b] Standard error in $\log_{10}$ form.

[c] Additional statistics for computation of confidence intervals:

$\Sigma (x-\bar{x})^2 = 13.3864$ and $\bar{x} = 4.0718$ for equations based on 71 trees and

$\Sigma (x-\bar{x})^2 = 1.6835$ and $\bar{x} = 4.4538$ for equations based on 35 trees.

Table 9.—Regression equations for estimating above-stump green cubic-foot volume of the total tree and its components for northern red oak trees 6 to 24 inches d.b.h., using d.b.h. and total height as independent variables

Cubic-foot volume (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y.x}$)[c]	Number trees sampled (N)
Total tree (excluding foliage):				
Wood	$Y = 0.002439 (D^2Th)^{1.00568}$	0.99	0.0382	71
Bark	$Y = 0.000633 (D^2Th)^{0.97091}$	.98	.0571	71
Wood & bark	$Y = 0.003052 (D^2Th)^{1.00014}$	.99	.0390	71
Stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.000633 (D^2Th)^{1.09537}$	.95	.0546	35
Bark	$Y = 0.000119 (D^2Th)^{1.06819}$	.93	.0676	35
Wood & bark	$Y = 0.000753 (D^2Th)^{1.09162}$	.95	.0537	35
Stem from stump to 8-inch d.i.b. top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.000745 (D^2Th)^{1.08867}$	.97	.0451	35
Bark	$Y = 0.000140 (D^2Th)^{1.06148}$	.93	.0650	35
Wood & bark	$Y = 0.000885 (D^2Th)^{1.08492}$	.97	.0449	35
Stem from stump to 4-inch d.i.b. top:				
Wood	$Y = 0.001763 (D^2Th)^{1.01258}$	.99	.0347	71
Bark	$Y = 0.000460 (D^2Th)^{0.95492}$	.99	.0517	71
Wood & bark	$Y = 0.002183 (D^2Th)^{1.00496}$	.99	.0339	71
Crown material (all branches and topwood < 4 inches d.i.b. excluding foliage):				
Wood	$Y = 0.000697 (D^2Th)^{0.97993}$	.92	.1295	71
Bark	$Y = 0.000188 (D^2Th)^{0.99205}$	.93	.1200	71
Wood & bark	$Y = 0.000889 (D^2Th)^{0.98263}$	.92	.1254	71
Crown material ≥ 4.0 inches d.o.b. (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.000000011 (D^2Th)^{1.96775}$	.76	.2490	35
Bark	$Y = 0.000000002 (D^2Th)^{1.98052}$	.80	.2239	35
Wood & bark	$Y = 0.000000013 (D^2Th)^{1.96991}$	.77	.2434	35

[a] $Y = b_0 (D^2Th)^{b_1}$

where:

Y = component volume in cubic feet,
D = d.b.h. in inches,
Th = total height of tree in feet,
b_0, b_1 = regression coefficients.

[b] Standard error in $\log_{10}$ form.

[c] Additional statistics for computation of confidence intervals:
$\Sigma(x-\bar{x})^2 = 13.3864$ and $\bar{x} = 4.0718$ for equations based on 71 trees and
$\Sigma(x-\bar{x})^2 = 1.6835$ and $\bar{x} = 4.4538$ for equations based on 35 trees.

Table 10.—Regression equations for estimating above-stump wood and bark green weights for northern red oak trees 6 to 24 inches d.b.h. and tree components using d.b.h., d.b.h. and height to 4-inch top, and d.b.h. and saw-log merchantable height as independent variables

Weight (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)	Sample mean of x[b] ($\bar{x}$)	Corrected sums of squares for x[b] $\Sigma(x - \bar{x})^2$	Number trees sampled (N)
Wood and bark in total tree, above stump						
	$Y = 5.44299\,(D^2)^{1.22075}$	0.99	0.0449	2.1559	9.0800	71
	$Y = 0.88448\,(D^2H4)^{0.87511}$	.99	.0506	3.9096	17.6201	71
	$Y = 5.97051\,(D^2)^{1.10049}(Mh)^{0.15495}$	.96	.0470	—	—	35
Wood and bark in stem stump to saw-log merchantable top						
	$Y = 2.78219\,(D^2)^{1.25916}$	.93	.0675	2.4697	1.2235	35
	$Y = 0.16293\,(D^2H4)^{0.99965}$	.96	.0524	4.3428	2.0010	35
	$Y = 0.76536\,(D^2)^{0.99153}(Mh)^{0.72285}$	.98	.0324	—	—	35
Wood and bark in stem from stump to 4-inch d.i.b. top						
	$Y = 4.11043\,(D^2)^{1.22077}$	.99	.0508	2.1559	9.0800	71
	$Y = 0.64173\,(D^2H4)^{0.87933}$	.99	.0352	3.9096	17.6201	71
	$Y = 4.02330\,(D^2)^{0.97341}(Mh)^{0.36878}$	.97	.0402	—	—	35
Wood and bark in crown (all branches and topwood ≥ 4-inches d.i.b.)						
	$Y = 1.34314\,(D^2)^{1.21542}$	.94	.1148	2.1559	9.0800	71
	$Y = 0.24995\,(D^2H4)^{0.85787}$	.90	.1409	3.9096	17.6201	71
	$Y = 2.00506\,(D^2)^{1.52753}(Mh)^{-0.55400}$	.82	.1231	—	—	35

[a] $Y = a(D^2)^b$ or $Y = a(D^2H4)^b$ or $Y = a(D^2)^{b_1}(Mh)^{b_2}$

where:

Y = component weight in pounds,
D = d.b.h. in inches,
H4 = tree height to 4-inch d.i.b. top in feet,
Mh = saw-log merchantable height in feet,
a, b_1, b_2 = regression coefficients.

[b] $\log_{10}$ form.

Table 11.—Regression equations for estimating above-stump wood volume for northern red oak trees 6 to 24 inches d.b.h. and tree components using d.b.h., d.b.h. and height to a 4-inch top, and d.b.h. and saw-log merchantable height as independent variables

Cubic-foot volume (Y)	Regression equation[a]	Coefficient of determination (R^2)	Standard error[b] ($S_{y \cdot x}$)	Sample mean of x[b] ($\bar{x}$)	Corrected sums of squares for x[b] $\Sigma(x - \bar{x})^2$	Number trees sampled (N)
Wood in total tree, above stump						
	$Y = 0.07138\,(D^2)^{1.21940}$	0.99	0.0447	2.1559	9.0800	71
	$Y = 0.01158\,(D^2H4)^{0.87451}$	.99	.0488	3.9096	17.6201	71
	$Y = 0.07462\,(D^2)^{1.09146}(Mh)^{0.17888}$	.96	.0470	—	—	35
Wood in stem from stump to saw-log merchantable top						
	$Y = 0.03550\,(D^2)^{1.26778}$	.93	.0679	2.4697	1.2235	35
	$Y = 0.00203\,(D^2H4)^{1.00689}$	.96	.0522	4.3428	2.0010	35
	$Y = 0.0982\,(D^2)^{1.00120}(Mh)^{0.72000}$	.98	.0336	—	—	35
Wood in stem from stump to 4-inch d.i.b. top						
	$Y = 0.05348\,(D^2)^{1.22531}$	.99	.0505	2.1559	9.0800	71
	$Y = 0.00828\,(D^2H4)^{0.88272}$	.99	.0338	3.9096	17.6201	71
	$Y = 0.05099\,(D^2)^{0.98216}(Mh)^{0.36979}$	.96	.0415	—	—	35
Wood in crown (all branches and topwood < 4 inches d.i.b.)						
	$Y = 0.01781\,(D^2)^{1.19740}$	.93	.1200	2.1559	9.0800	71
	$Y = 0.00341\,(D^2H4)^{0.84488}$	.90	.1442	3.9096	17.6201	71
	$Y = 0.02450\,(D^2)^{1.51110}(Mh)^{-0.53521}$	.80	.1299	—	—	35

[a] $Y = a(D^2)^b$ or $Y = a(D^2H4)^b$ or $Y = a(D^2)^{b_1}(Mh)^{b_2}$

where:

Y = component volume in cubic feet,
D = d.b.h. in inches,
H4 = tree height to 4-inch d.i.b. top in feet,
Mh = saw-log merchantable height in feet,
a, b_1, b_2 = regression coefficients.

[b] $\log_{10}$ form.

Table 12.—Predicted green weight of total-tree wood and bark, above stump, for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
				Pounds				
				WOOD AND BARK[3]				
5	243	292	341	391				
6	351	422	493	564				
7	479	576	672	769	866			
8	627	753	879	1,006	1,133			
9	795	955	1,115	1,275	1,436	1,596		
10	982	1,180	1,378	1,576	1,775	1,973		
11	1,190	1,430	1,670	1,910	2,150	2,391	2,632	
12	1,418	1,703	1,989	2,275	2,562	2,849	3,135	
13		2,001	2,337	2,673	3,010	3,347	3,684	4,021
14		2,323	2,713	3,103	3,494	3,885	4,276	4,668
15		2,669	3,117	3,566	4,015	4,464	4,913	5,363
16			3,550	4,061	4,572	5,083	5,595	6,107
17			4,011	4,588	5,165	5,743	6,321	6,900
18			4,500	5,147	5,795	6,443	7,092	7,741
19			5,017	5,739	6,461	7,184	7,908	8,631
20			5,563	6,363	7,164	7,966	8,768	9,570
21			6,137	7,020	7,904	8,788	9,673	10,558
22			6,740	7,709	8,680	9,651	10,622	11,595
23			7,371	8,431	9,492	10,554	11,617	12,680
24			8,030	9,185	10,341	11,498	12,656	13,814
25			8,718	9,972	11,227	12,483	13,740	14,997
				WOOD[4]				
5	203	244	286	327				
6	294	354	414	473				
7	402	483	565	647	729			
8	527	634	741	848	955			
9	669	804	940	1,077	1,213	1,350		
10	828	996	1,164	1,333	1,502	1,671		
11	1,004	1,208	1,412	1,617	1,822	2,027	2,232	
12	1,198	1,441	1,684	1,928	2,173	2,418	2,663	
13		1,695	1,981	2,268	2,555	2,843	3,132	3,420
14		1,969	2,302	2,635	2,970	3,304	3,639	3,974
15		2,265	2,647	3,031	3,415	3,800	4,185	4,571
16			3,017	3,454	3,892	4,331	4,770	5,209
17			3,412	3,906	4,401	4,897	5,393	5,890
18			3,831	4,386	4,941	5,498	6,055	6,613
19			4,274	4,893	5,513	6,135	6,756	7,379
20			4,742	5,429	6,117	6,806	7,497	8,187
21			5,235	5,993	6,753	7,514	8,276	9,038
22			5,753	6,586	7,421	8,257	9,094	9,932
23			6,295	7,207	8,120	9,035	9,951	10,868
24			6,862	7,856	8,851	9,848	10,847	11,847
25			7,453	8,533	9,615	10,698	11,782	12,868

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.18579 (D^2Th)^{1.00655}$

[4] $Y = 0.14803 (D^2Th)^{1.01315}$

Table 13.—Predicted green weight of wood and bark in saw-log stem to 8-inch d.i.b. or saw-log merchantable top for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)						
	60	70	80	90	100	110	120
				Pounds			
				WOOD AND BARK[3]			
11	810	958	1,108	1,259	1,412	1,566	
12	979	1,158	1,338	1,521	1,706	1,893	
13	1,165	1,378	1,593	1,811	2,031	2,253	2,476
14	1,369	1,619	1,872	2,128	2,386	2,647	2,909
15	1,590	1,881	2,175	2,472	2,772	3,075	3,380
16		2,164	2,503	2,845	3,190	3,539	3,890
17		2,469	2,855	3,246	3,640	4,038	4,438
18		2,796	3,234	3,676	4,122	4,572	5,026
19		3,145	3,637	4,134	4,636	5,143	5,653
20		3,517	4,067	4,622	5,184	5,750	6,321
21		3,911	4,522	5,140	5,764	6,394	7,028
22		4,327	5,003	5,687	6,378	7,075	7,777
23		4,766	5,511	6,265	7,026	7,793	8,567
24		5,229	6,046	6,873	7,707	8,549	9,398
25		5,714	6,608	7,511	8,423	9,343	10,270
				WOOD[4]			
11	712	842	974	1,107	1,242	1,377	
12	860	1,018	1,177	1,338	1,501	1,665	
13	1,024	1,211	1,401	1,593	1,787	1,982	2,179
14	1.204	1,424	1,647	1,872	2,100	2,329	2,561
15	1,399	1,655	1,914	2,176	2,440	2,707	2,976
16		1,904	2,203	2,504	2,809	3,116	3,426
17		2,173	2,514	2,858	3,205	3,556	3,909
18		2,462	2,847	3,237	3,630	4,027	4,428
19		2,769	3,203	3,641	4,084	4,531	4,981
20		3,097	3,581	4,072	4,567	5,067	5,570
21		3,444	3,983	4,528	5,079	5,635	6,195
22		3,811	4,408	5,011	5,621	6,236	6,856
23		4,199	4,856	5,521	6,192	6,870	7,553
24		4,607	5,328	6,057	6,794	7,537	8,287
25		5,035	5,824	6,621	7,426	8,238	9,057

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.05116(D^2Th)^{1.08771}$.

[4] $Y = 0.04433(D^2Th)^{1.08928}$.

Table 14.—Predicted green weight of wood and bark in stem to 4-inch d.i.b. top for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
				Pounds				
				WOOD AND BARK[3]				
5	183	220	257	294				
6	264	317	371	424				
7	360	433	506	579	652			
8	472	567	662	758	853			
9	598	719	840	961	1,082	1,203		
10	740	889	1,039	1,188	1,338	1,488		
11	897	1,078	1,259	1,440	1,622	1,804	1,986	
12	1,069	1,284	1,500	1,717	1,933	2,150	2,367	
13		1,509	1,763	2,018	2,272	2,527	2,782	3,037
14		1,753	2,048	2,343	2,639	2,935	3,231	3,527
15		2,015	2,354	2,693	3,033	3,373	3,713	4,054
16			2,681	3,067	3,454	3,842	4,230	4,618
17			3,030	3,467	3,904	4,342	4,780	5,218
18			3,400	3,890	4,381	4,872	5,364	5,856
19			3,792	4,339	4,886	5,434	5,982	6,531
20			4,205	4,812	5,419	6,026	6,635	7,243
21			4,640	5,309	5,979	6,650	7,321	7,993
22			5,097	5,832	6,568	7,304	8,041	8,779
23			5,575	6,379	7,184	7,989	8,796	9,603
24			6,075	6,951	7,828	8,706	9,584	10,464
25			6,597	7,548	8,500	9,453	10,407	11,362
				WOOD[4]				
5	156	188	220	252				
6	226	272	319	365				
7	310	373	436	500	563			
8	406	489	572	656	739			
9	516	622	727	833	939	1,045		
10	640	770	901	1,032	1,164	1,295		
11	777	935	1,094	1,253	1,413	1,573	1,733	
12	927	1,116	1,306	1,496	1,686	1,877	2,068	
13		1,314	1,537	1,760	1,985	2,209	2,434	2,659
14		1,528	1,787	2,047	2,308	2,569	2,830	3,092
15		1,758	2,056	2,356	2,655	2,956	3,257	3,558
16			2,345	2,686	3,028	3,371	3,714	4,058
17			2,653	3,039	3,426	3,813	4,202	4,590
18			2,980	3,414	3,848	4,284	4,720	5,157
19			3,326	3,811	4,296	4,782	5,269	5,756
20			3,692	4,230	4,768	5,308	5,848	6,390
21			4,078	4,671	5,266	5,862	6,459	7,056
22			4,483	5,135	5,789	6,444	7,100	7,757
23			4,907	5,621	6,337	7,054	7,772	8,491
24			5,351	6,130	6,910	7,692	8,475	9,260
25			5,814	6,661	7,508	8,358	9,209	10,062

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.13724(D^2Th)^{1.00877}$.

[4] $Y = 0.11034(D^2Th)^{1.01741}$.

Table 15.—Predicted green weight of wood and bark in crown for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
				Pounds				
				WOOD AND BARK[3]				
5	60	72	96					
6	87	104	121	138				
7	118	141	164	188	211			
8	153	184	215	245	275			
9	194	233	271	310	348	387		
10	239	287	334	382	429	477		
11	289	347	404	462	519	576	634	
12	344	412	481	549	617	685	753	
13		483	564	644	724	804	884	963
14		560	653	746	839	931	1,024	1,116
15		643	749	856	962	1,068	1,175	1,281
16			852	973	1,094	1,215	1,335	1,456
17			961	1,098	1,234	1,370	1,507	1,643
18			1,077	1,230	1,383	1,535	1,688	1,841
19			1,199	1,369	1,540	1,710	1,880	2,050
20			1,328	1,517	1,705	1,893	2,082	2,270
21			1,463	1,671	1,879	2,087	3,294	2,501
22			1,605	1,833	2,061	2,289	2,516	2,744
23			1,754	2,003	2,252	2,500	2,749	2,998
24			1,909	2,180	2,451	2,721	2,992	3,263
25			2,070	2,364	2,658	2,952	3,245	3,539
				WOOD[4]				
5	47	56	65	74				
6	67	80	94	107				
7	91	109	127	145	163			
8	119	142	166	190	213			
9	150	180	210	240	269	299		
10	185	222	259	295	332	369		
11	244	268	313	357	401	446	490	
12	266	319	372	424	477	530	582	
13		374	436	498	559	621	683	744
14		433	505	577	648	720	791	863
15		497	579	661	743	825	907	989
16			658	752	845	938	1,032	1,125
17			743	848	953	1,059	1,164	1,269
18			832	950	1,068	1,186	1,304	1,422
19			926	1,058	1,189	1,321	1,452	1,583
20			1,026	1,171	1,317	1,462	1,608	1,753
21			1,130	1,291	1,451	1,611	1,771	1,931
22			1,240	1,416	1,592	1,767	1,943	2,118
23			1,354	1,547	1,739	1,931	2,122	2,314
24			1,474	1,683	1,892	2,101	2,310	2,518
25			1,598	1,825	2,052	2,279	2,505	2,731

[1] Blocked-in area indicates range of data.

[2] Includues 1-foot stump allowance.

[3] $Y = 0.05004\ (D^2Th)^{0.99476}$.

[4] $Y = 0.03901\ (D^2Th)^{0.99387}$.

Table 16.—Predicted volume of above-stump total-tree wood and bark for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
	Cubic feet							
	WOOD AND BARK[3]							
5	3.8	4.6	5.3	6.1				
6	5.5	6.6	7.7	8.8				
7	7.5	9.0	10.5	12.0	13.5			
8	9.8	11.7	13.7	15.6	17.6			
9	12.4	14.8	17.3	19.8	22.3	24.7		
10	15.3	18.3	21.4	24.4	27.5	30.5		
11	18.5	22.2	25.9	29.6	33.3	37.0	40.6	
12	22.0	26.4	30.8	35.2	39.6	44.0	48.4	
13		31.0	36.1	41.3	46.5	51.6	56.8	61.9
14		35.9	41.9	47.9	53.9	59.9	65.8	71.8
15		41.2	48.1	55.0	61.8	68.7	75.6	82.5
16			54.7	62.6	70.4	78.2	86.0	93.8
17			61.8	70.6	79.4	88.3	97.1	105.9
18			69.3	79.2	89.1	99.0	108.9	118.8
19			77.2	88.2	99.2	110.3	121.3	132.3
20			85.5	97.7	110.0	122.2	134.4	146.6
21			94.3	107.8	121.2	134.7	148.2	161.7
22			103.5	118.3	133.1	147.8	162.6	177.4
23			113.1	129.3	145.4	161.6	177.8	193.9
24			123.2	140.8	158.4	175.9	193.5	211.1
25			133.6	152.7	171.8	190.9	210.0	229.1
	WOOD[4]							
5	3.2	3.8	4.5	5.1				
6	4.6	5.5	6.4	7.3				
7	6.2	7.5	8.8	10.0	11.3			
8	8.2	9.8	11.5	13.1	14.8			
9	10.4	12.4	14.5	16.6	18.7	20.8		
10	12.8	15.4	18.0	20.5	23.1	25.7		
11	15.5	18.6	21.7	24.9	28.0	31.1	34.3	
12	18.5	22.2	25.9	29.6	33.4	37.1	40.8	
13		26.1	30.4	34.8	39.2	43.6	47.9	52.3
14		30.3	35.3	40.4	45.5	50.6	55.7	60.7
15		34.8	40.6	46.4	52.3	58.1	63.9	69.8
16			46.2	52.8	59.5	66.1	72.8	79.5
17			52.2	59.7	67.2	74.7	82.2	89.8
18			58.6	67.0	75.4	83.8	92.3	100.7
19			65.3	74.7	84.1	93.5	102.9	112.3
20			72.4	82.8	93.2	103.6	114.0	124.5
21			79.8	91.3	102.8	114.3	125.8	137.3
22			87.7	100.3	112.9	125.5	138.1	150.8
23			95.9	109.7	123.4	137.2	151.0	164.9
24			104.4	119.5	134.5	149.5	164.5	179.6
25			113.4	129.7	146.0	162.3	178.6	195.0

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.003050\,(D^2Th)^{1.00014}$.

[4] $Y = 0.002439\,(D^2Th)^{1.00568}$.

Table 17.—Predicted volume of wood and bark in saw-log stem to 8-inch d.i.b. or saw-log merchantable top for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)						
	60	70	80	90	100	110	120
	Cubic feet						
	WOOD AND BARK[3]						
11	12.3	14.6	16.9	19.2	21.6	23.9	
12	14.9	17.7	20.4	23.2	26.1	28.9	
13	17.8	21.0	24.3	27.7	31.0	34.5	37.9
14	20.9	24.7	28.6	32.5	36.5	40.5	44.5
15	24.3	28.7	33.3	37.8	42.4	47.1	51.8
16		33.1	38.3	43.5	48.9	54.2	59.6
17		37.8	43.7	49.7	55.8	61.9	68.1
18		42.8	49.5	56.3	63.2	70.1	77.1
19		48.2	55.7	63.4	71.1	78.9	86.8
20		53.9	62.3	70.9	79.5	88.2	97.0
21		59.9	69.3	78.9	88.5	98.2	107.9
22		66.3	76.7	87.3	97.9	108.7	119.5
23		73.1	84.6	96.2	107.9	119.7	131.7
24		80.2	92.8	105.5	118.4	131.4	144.5
25		87.7	101.5	115.4	129.4	143.6	157.9
	WOOD[4]						
11	10.7	12.7	14.7	16.7	18.8	20.8	
12	13.0	15.4	17.8	20.2	22.7	25.2	27.7
13	15.5	18.3	21.2	24.1	27.1	30.0	33.1
14	18.2	21.5	24.9	28.4	31.8	35.3	38.9
15	21.2	25.1	29.0	33.0	37.0	41.1	45.2
16		28.9	33.4	38.0	42.7	47.4	52.1
17		33.0	38.2	43.4	48.7	54.1	59.5
18		37.4	43.2	49.2	55.2	61.3	67.4
19		42.1	48.7	55.4	62.2	69.0	75.9
20		47.1	54.5	62.0	69.6	77.2	84.9
21		52.4	60.6	69.0	77.4	85.9	94.5
22		58.0	67.1	76.4	85.7	95.1	104.7
23		63.9	74.0	84.2	94.5	104.9	115.4
24		70.2	81.2	92.4	103.7	115.1	126.6
25		76.7	88.8	101.1	113.4	125.9	138.5

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.000753 (D^2Th)^{1.09162}$.

[4] $Y = 0.000633 (D^2Th)^{1.09537}$.

Table 18.—Predicted volume of wood and bark in stem to 4-inch d.i.b. top for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
				Cubic feet				
				WOOD AND BARK[3]				
5	2.8	3.4	4.0	4.5				
6	4.1	4.9	5.7	6.5				
7	5.6	6.7	7.8	8.9	10.0			
8	7.3	8.7	10.2	11.7	13.1			
9	9.2	11.1	12.9	14.8	16.6	18.5		
10	11.4	13.7	16.0	18.3	20.6	22.9		
11	13.8	16.6	19.3	22.1	24.9	27.7	30.5	
12	16.4	19.7	23.0	26.3	29.7	33.0	36.3	
13		23.2	27.1	30.9	34.8	38.7	42.6	46.5
14		26.9	31.4	35.9	40.4	44.9	49.5	54.0
15		30.9	36.1	41.3	46.4	51.6	56.8	62.0
16			41.1	47.0	52.9	58.8	64.7	70.6
17			46.4	53.0	59.7	66.4	73.1	79.7
18			52.0	59.5	67.0	74.5	82.0	89.4
19			58.0	66.3	74.7	83.0	91.4	99.7
20			64.3	73.5	82.8	92.0	101.3	110.5
21			70.9	81.1	91.3	101.5	111.7	121.9
22			77.9	89.1	100.3	111.5	122.7	133.9
23			85.2	97.4	109.6	121.9	134.1	146.4
24			92.8	106.1	119.4	132.8	146.1	159.5
25			100.7	115.2	129.6	144.1	158.6	173.1
				WOOD[4]				
5	2.4	2.9	3.4	3.9				
6	3.5	4.2	4.9	5.6				
7	4.8	5.7	6.7	7.7	8.6			
8	6.2	7.5	8.8	10.1	11.3			
9	7.9	9.5	11.1	12.8	14.4	16.0		
10	9.8	11.8	13.8	15.8	17.8	19.8		
11	11.9	14.3	16.7	19.2	21.6	24.0	26.4	
12	14.2	17.1	20.0	22.8	25.7	28.6	31.5	
13		20.1	23.5	26.9	30.3	33.7	37.1	40.5
14		23.3	27.3	31.2	35.2	39.1	43.1	47.1
15		26.8	31.4	35.9	40.4	45.0	49.6	54.1
16			35.7	40.9	46.1	51.3	56.5	61.7
17			40.4	46.3	52.1	58.0	63.9	69.7
18			45.4	51.9	58.5	65.1	71.7	78.3
19			50.6	57.9	65.3	72.6	80.0	87.4
20			56.2	64.3	72.4	80.6	88.7	96.9
21			62.0	71.0	79.9	88.9	98.0	107.0
22			68.1	78.0	87.8	97.7	107.6	117.5
23			74.5	85.3	96.1	106.9	117.8	128.6
24			81.2	93.0	104.8	116.6	128.4	140.2
25			88.2	101.0	113.8	126.6	139.4	152.3

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.002183\,(D^2Th)^{1.00496}$.

[4] $Y = 0.001763\,(D^2Th)^{1.01258}$.

Table 19.—Predicted volume of wood and bark in crown for northern red oak trees[1]

D.b.h. (inches)	Total-tree height[2] (feet)							
	50	60	70	80	90	100	110	120
	Cubic feet							
	WOOD AND BARK[3]							
5	1.0	1.2	1.4	1.6				
6	1.4	1.7	2.0	2.2				
7	1.9	2.3	2.6	3.0	3.4			
8	2.5	3.0	3.4	3.9	4.4			
9	3.1	3.7	4.3	4.9	5.6	6.2		
10	3.8	4.6	5.3	6.1	6.8	7.6		
11	4.6	5.5	6.4	7.3	8.2	9.1	10.0	
12	5.5	6.6	7.6	8.7	9.8	10.8	11.9	
13		7.7	8.9	10.2	11.4	12.7	13.9	15.2
14		8.9	10.3	11.8	13.2	14.7	16.1	17.6
15		10.2	11.8	13.5	15.2	16.8	18.5	20.1
16			13.4	15.3	17.2	19.1	21.0	22.8
17			15.1	17.3	19.4	21.5	23.6	25.7
18			16.9	19.3	21.7	24.0	26.4	28.8
19			18.8	21.5	24.1	26.7	29.4	32.0
20			20.8	23.8	26.7	29.6	32.5	35.4
21			22.9	26.1	29.4	32.6	35.8	38.9
22			25.1	28.7	32.2	35.7	39.2	42.7
23			27.4	31.3	35.1	38.9	42.8	46.6
24			29.8	34.0	38.2	42.3	46.5	50.6
25			32.3	36.8	41.4	45.9	50.4	54.9
	WOOD[4]							
5	0.8	0.9	1.0	1.2				
6	1.1	1.3	1.5	1.7				
7	1.5	1.7	2.0	2.3	2.6			
8	1.9	2.3	2.6	3.0	3.4			
9	2.4	2.9	3.3	3.8	4.3	4.7		
10	2.9	3.5	4.1	4.7	5.2	5.8		
11	3.5	4.2	4.9	5.6	6.3	7.0	7.7	
12	4.2	5.0	5.8	6.7	7.5	8.3	9.1	
13		5.9	6.8	7.8	8.7	9.7	10.6	11.6
14		6.8	7.9	9.0	10.1	11.2	12.3	13.4
15		7.8	9.0	10.3	11.6	12.8	14.1	15.3
16			10.3	11.7	13.1	14.6	16.0	17.4
17			11.6	13.2	14.8	16.4	18.0	19.6
18			12.9	14.7	16.5	18.3	20.1	21.9
19			14.4	16.4	18.4	20.4	22.4	24.4
20			15.9	18.1	20.3	22.5	24.7	26.9
21			17.5	19.9	22.4	24.8	27.2	29.7
22			19.2	21.8	24.5	27.2	29.8	32.5
23			20.9	23.8	26.7	29.6	32.5	35.4
24			22.7	25.9	29.1	32.2	35.4	38.5
25			24.6	28.0	31.5	34.9	38.3	41.7

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $Y = 0.000889 (D^2Th)^{0.98263}$.

[4] $Y = 0.000697 (D^2Th)^{0.97993}$.

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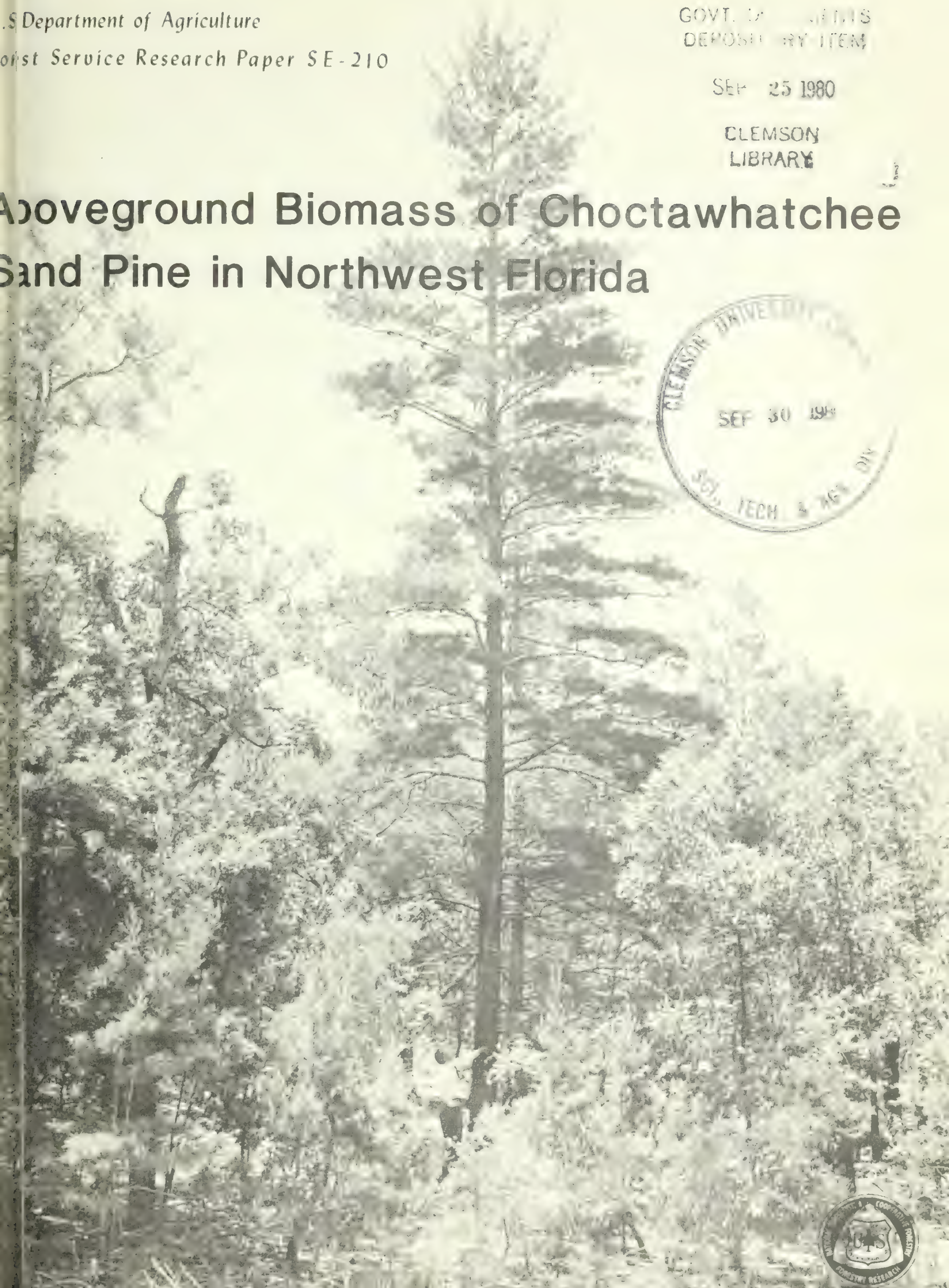

Conversion factors: English to metric

Multiply	*By*	*To obtain*
Inches	2.540	centimeters
Feet	.3048	meters
Pounds	.4536	kilograms
Cubic feet	.02832	cubic meters
Pounds per cubic foot	16.02	kilograms per cubic meter

All English units of measure in this report can be converted to metric units by multiplying the appropriate conversion factor listed above.

July 1980

Southeastern Forest Experiment Station
Asheville, North Carolina

Aboveground Biomass of Choctawhatchee Sand Pine in Northwest Florida[1]

by
Michael A. Taras[2]

ABSTRACT.—Choctawhatchee sand pine trees 4 to 14 inches d.b.h. were selected from a natural, uneven-aged stand in northwest Florida to determine the weight and volume of aboveground biomass. On the average, 85 percent of the green weight of the total tree was wood, 11 percent bark, and 4 percent needles. The average tree sampled had 82 percent of its wood in the stem and 18 percent in the crown. Specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components. Tables developed from regression equations predict weight and cubic-foot volume of the total tree and its components by d.b.h. and total height classes.

Keywords: *Pinus clausa* var. *immuginata* Ward, weight, volume, equations, component proportions.

This is the fifth in a series of reports on the aboveground biomass of southern pines. It contains information on Choctawhatchee sand pine (*Pinus clausa* var. *immuginata* Ward). The first four papers reported biomass for the four major southern pines (Taras and Clark 1975; Clark and Taras 1976; Taras and Clark 1977; and Taras and Phillips 1978).

This Paper reports weight and volume of various tree components (wood, bark, crown, branches, and foliage) as well as equations for predicting these values. The term "total tree" in this study refers only to the aboveground portion of the tree and does not include stump and roots.

PROCEDURE

Field

A stratified random sample of 36 trees was selected from a natural, uneven-aged Choctawhatchee sand pine stand on Eglin Air Force Base in northwest Florida. Site index (age 50) averaged about 50. Six trees in each even-inch d.b.h. class from 4 to 14 inches were randomly selected. Means and ranges in tree dimensions are shown in table 1.

Sample trees were felled and limbed and the main stem of each tree was bucked into 3- to 5-foot segments and weighed to the nearest one-quarter pound on a portable balance. Separate weights were recorded for the saw-log portion of the main stem to a 6-inch d.i.b. top and for the pulpwood portion of the stem to a 3-inch d.o.b. top. Sample branches were selected from the lower, middle, and upper portions of the crown. These were weighed and stripped of their needles, and the needles were weighed to establish the foliage: branch ratio. The remainder of the crown (needles and branches) was weighed together. Needle weight for the whole tree was computed by applying the needle:branch ratio developed from the branch samples. Dead branches were weighed separately but were not included in calculations for the total tree in this report.

Moisture content and specific gravity of wood and bark were determined from disks removed at the butt of each tree, at d.b.h., and at quarter points in the stem to a 3-inch d.o.b. top. Disks were also taken from the branches randomly selected from the lower, middle, and upper portions of the crown. Each disk sample was sealed in a plastic bag for subsequent laboratory analysis. Samples of needles and dead branches were selected for determination of moisture contents of these components.

Laboratory

Each sample disk was weighed and diameters were measured with and without bark, and spe-

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[1] This study was conducted in cooperation with the Forestry Division of Eglin Air Force Base, Fort Walton Beach, Fla.

[2] The author is now Professor of Forestry, College of Forest and Recreation Resources, Clemson University, Clemson, S.C. 29631.

Table 1.—Means and ranges in dimensions of sample Choctawhatchee sand pines, by d.b.h. class

D.b.h. class (inches)	Sample trees	D.b.h.		Total height		Age	
		Average	Range	Average	Range	Average	Range
	Number	..... *Inches*		...... *Feet*		...... *Years*	
4	6	4.2	3.9– 4.4	33	24–44	46	37–52
6	6	6.1	5.7– 6.4	47	41–56	54	46–59
8	6	8.1	7.8– 8.4	50	45–56	53	37–59
10	6	10.0	9.6–10.3	57	53–61	59	53–66
12	6	12.1	11.6–12.5	60	53–63	58	54–61
14	6	14.1	13.6–14.7	64	56–67	73	60–88
All classes	36	9.1	3.9–14.7	52	24–67	57	37–88

cific gravity was determined for each component on a green-volume and ovendry-weight basis. Moisture content samples were dried to a constant weight at 103° C, and moisture content was computed on an ovendry basis. Percentage of bark was determined from the disk samples on a green-weight basis. Values for moisture content (MC), specific gravity (SG), and percentage of bark in the stem, branches, and total tree were calculated by weighting disk values in proportion to the volume of the component each represented. Weighted moisture content values were used to convert component green weights to ovendry weights.

Green weights per cubic foot of wood and bark were computed from the weighted values for specific gravity and moisture content with the equation:

$$\text{Green wt/ft}^3 = \left[1 + \frac{\text{weighted MC in \%}}{100}\right](\text{weighted SG})(62.4) \quad (1)$$

The green cubic-foot volumes of wood and bark were computed by dividing a component's weight by its green weight per cubic foot. Green cubic-foot volume of wood and bark combined was computed by adding the green volume of wood to the green volume of bark.

Analysis

Regression equations for predicting green and dry weights of wood, bark, and needles in the total tree and its components were developed with d.b.h. and total height as independent variables. Equations were also developed to predict green cubic-foot volumes of wood and bark separately and combined. Total-tree and tree component weights and volumes were estimated with the equation:

$$Y = b_0 + b_1 D^2 Th + e \quad (2)$$

where:

Y = predicted weight or volume of component
D = d.b.h. in inches
Th = total tree height in feet
e = experimental error

and

b_0, b_1 = coefficients.

Grouping of the data into D^2Th classes indicated that the variance of Y increased with increasing D^2Th. Therefore, a logarithmic transformation was used to make the variance more nearly homogeneous and meet this basic assumption of regression analysis. The final form of the equation used to predict weight and volume of the total tree and each component sampled was:

$$\text{Log}_{10} Y = b_0 + b_1 \text{Log}_{10}(D^2 Th) \quad (3)$$

SAMPLE TREE CHARACTERISTICS

Total-Tree Biomass

Green weight of the total tree ranged from 126 pounds for 4-inch trees to 2,372 pounds for 14-inch trees. On the average, the trees sampled had 85 percent of their green weight in wood, 11 percent in bark, and 4 percent in needles. This distribution of wood, bark, and needles is similar to those reported for the major southern pines. The proportion of tree weight in wood increased and the proportion in bark decreased sharply between the 4-inch and the 6-inch d.b.h. class, then remained relatively constant to the 14-inch class. The proportion of needles was highest (7 percent) in the 4-inch class and was consistently between 3 and 4 percent for all other diameter classes. Proportions of the various tree components computed on a dry basis varied slightly from those computed on a green basis because of differences in component moisture content (table 2).

When the trees are viewed as being composed of stem and crown, proportion of tree weight in the stem increases and that in branches decreases from the 4-inch d.b.h. class to the 6-inch class and then increases with tree size (table 3). The stem contained an average of 76 percent of the tree green weight, and the crown 24 percent. The proportion of biomass in the stems of Choctawhatchee sand pines is 5 to 8 percent lower than that reported for the four major species of southern pine. Since the needle proportion was the same as reported for other southern pines (about 4 percent), the primary cause for the difference in crown biomass is the greater weight of branch material in sand pine.

The green and dry weights of all wood in the tree and the distribution of wood throughout the tree are presented in table 4. On the average, 82 percent of green weight was in the main stem (to a 3-inch d.o.b. top), and 18 percent was in the branches. The proportion of wood increased in the main stem from the 4-inch d.b.h. class to the 6-inch class and then decreased as tree size increased. Branchwood proportions decreased be-

Table 2.—Average green and dry weights of the total tree and proportions of the tree in wood, bark, and needles for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total-tree green weight	Tree component proportions (green)			Total-tree dry weight	Tree component proportions (dry)		
				Wood	Bark	Needles		Wood	Bark	Needles
	Feet	*Number*	*Pounds*	.... *Percent*			*Pounds*	.... *Percent*		
4	33	6	126	75	18	7	63	80	15	5
6	47	6	353	85	12	3	178	88	10	2
8	50	6	610	84	12	4	298	86	10	4
10	57	6	1,167	85	11	4	580	88	9	3
12	60	6	1,661	85	12	3	874	88	9	3
14	64	6	2,372	87	10	3	1,257	90	7	3
Average	—	—	1,048	85	11	4	542	88	9	3

Table 3.—Average green and dry weights of the total tree and proportions of the tree in the main stem[1] and crown (branches and needles) for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total-tree green weight	Tree component proportions (green)			Total-tree dry weight	Tree component proportions (dry)		
				Stem	Crown			Stem	Crown	
					Branches	Needles			Branches	Needles
	Feet	*Number*	*Pounds*	.... *Percent*			*Pounds*	.... *Percent*		
4	33	6	126	61	32	7	63	68	27	5
6	47	6	353	80	17	3	178	84	14	2
8	50	6	610	79	17	4	298	83	13	4
10	57	6	1,167	79	17	4	580	82	15	3
12	60	6	1,661	76	21	3	874	79	18	3
14	64	6	2,372	76	21	3	1,257	80	17	3
Average	—	—	1,048	76	20	4	542	80	17	3

[1] Stem material to 3-inch d.o.b. top.

Table 4.—Average green and dry weights of wood in the total tree and distribution of wood in the main stem[1] and branches for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total-tree wood weight	Proportion of wood in—			
				Main stem			Branches
				Saw log	Pulpwood	Total stem	
	Feet	*Number*	*Pounds*	*Percent*			
			GREEN				
4	33	6	95	—	70	70	30
6	47	6	299	—	85	85	15
8	50	6	509	42	43	85	15
10	57	6	995	68	16	84	16
12	60	6	1,408	74	7	81	19
14	64	6	2,069	75	6	81	19
Average	—	—	896	70	12	82	18
			DRY				
4	33	6	52	—	73	73	27
6	47	6	156	—	88	88	12
8	50	6	257	45	42	87	13
10	57	6	510	71	15	86	14
12	60	6	768	76	7	83	17
14	64	6	1,138	79	5	84	16
Average	—	—	480	73	12	85	15

[1] Stem material to 3-inch d.o.b. top.

tween the 4- and 6-inch d.b.h. classes and then increased as tree size increased. The proportion of wood in the pulpwood section of a tree decreased, and proportion in the saw-log section increased as tree size increased. On the average, the trees contained 70 percent of their green wood in saw logs and 12 percent in pulpwood. The proportion of branches in Choctawhatchee sand pine is 5 to 7 percent greater than that found in the major species of southern pine because sand pines have a heavier branching habit.

The weight and distribution of bark in the tree are presented in table 5. On the average, 44 percent of all green bark in the tree was in the saw logs, 16 percent in the pulpwood, and 40 percent in the branches. In comparing the bark proportions with similar computations made from the major southern pine species, we find bark proportion of the crown to be 7 to 11 percent greater in sand pine. This difference is due to the greater proportion of branches in the crown of this species.

Crown Biomass

When the crown was analyzed as a separate entity composed of branchwood, branchbark, and needles, the proportion of crown weight in wood increased, the proportion of crown bark decreased, and the proportion of needles decreased as tree size increased (table 6). On the average, 66 percent of the green weight of the crown was wood, 19 percent was bark, and 15 percent was needles. Compared to the crowns of the major southern pine species, Choctawhatchee sand pine has a higher percentage of wood in the crown, about the same amount of bark, and fewer needles.

The dead branch components of these trees were not included in the total-tree weight or the weight of the crown even though the weight data on this component were collected. The reason it was not included was that it was felt that a high proportion of this material would be lost in felling and skidding and not recoverable. Equations were developed, however, for predicting this component (*see* tables 9 and 10).

Main Stem Biomass

When the main stem was analyzed separately, the proportion of stem weight in wood increased and the proportion of bark decreased as tree size increased (table 7). On the average, 91 percent of the green weight of the main stem was wood, and 9 percent was bark. Similar proportions of wood and bark in the main stem have been reported for the four major species of southern pine.

Table 5.—Average green and dry weights of bark in the total tree and distribution of bark in the main stem[1] and branches for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Total-tree bark weight	Proportion of bark in—			
				Main stem			Branches
				Saw log	Pulpwood	Total stem	
	Feet	*Number*	*Pounds*	....	*Percent*	....	
			GREEN				
4	33	6	22	—	48	48	52
6	47	6	43	—	67	67	33
8	50	6	74	34	36	70	30
10	57	6	126	50	14	64	36
12	60	6	197	53	6	59	41
14	64	6	225	50	5	55	45
Average	—	—	115	44	16	60	40
			DRY				
4	33	6	9	—	59	59	41
6	47	6	18	—	74	74	26
8	50	6	30	41	34	75	25
10	57	6	52	57	12	69	31
12	60	6	83	61	5	66	34
14	64	6	87	54	5	59	41
Average	—	—	44	50	16	66	34

[1] Stem material to 3-inch d.o.b. top.

Table 6.—Average green and dry weights of the crown and proportion of the crown in wood, bark, and needles for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Crown weight (green)	Crown proportion (green)—			Crown weight (dry)	Crown proportion (dry)—		
				Branchwood	Branchbark	Needles		Branchwood	Branchbark	Needles
	Feet	*Number*	*Pounds*	....	*Percent*	....	*Pounds*	....	*Percent*	....
4	33	6	49	59	24	17	21	65	19	16
6	47	6	71	64	20	16	28	68	16	16
8	50	6	126	61	18	21	51	64	15	21
10	57	6	248	63	18	19	103	67	15	18
12	60	6	407	66	20	14	182	72	15	13
14	64	6	571	68	18	14	248	73	14	13
Average	—	—	245	66	19	15	106	70	15	15

Table 7.—Average green and dry weights of the stem[1] and proportion of the stem in wood and bark for Choctawhatchee sand pines 4 to 14 inches d.b.h.

D.b.h. class (inches)	Average total height	Sample trees	Main stem weight (green)	Stem proportion in green—		Main stem weight (dry)	Stem proportion in dry—	
				Wood	Bark		Wood	Bark
	Feet	*Number*	*Pounds*	.... *Percent*		*Pounds*	.... *Percent*	
4	33	6	77	86	14	42	87	13
6	47	6	283	90	10	150	91	9
8	50	6	484	89	11	248	91	9
10	57	6	919	91	9	477	93	7
12	60	6	1,254	91	9	691	92	8
14	64	6	1,802	93	7	1,009	95	5
Average	—	—	803	91	9	436	93	7

[1] Stem material to 3-inch d.o.b. top.

Physical Properties

Wood and bark specific gravity, moisture content, and green weight per cubic foot in the total tree and its components are presented in table 8. Wood specific gravity for the total tree averaged 0.475. Wood specific gravity of the saw-log portion of the tree and the main stem as a whole averaged 0.485, which is the average reported in a wood density survey of the species (Clark and Taras 1969). Specific gravity of the pulpwood portion of the tree averaged 0.455, which is slightly lower than the saw-log portion of the tree but slightly higher than that for the

Table 8.—Average wood and bark specific gravity, moisture content, and green weight per cubic foot for Choctawhatchee sand pine trees and tree components

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	*Pounds*
	WOOD		
Total tree	0.475 ± 0.025	91 ± 14	56.4 ± 3.4
Saw log	.485 ± .030	81 ± 11	54.7 ± 3.9
Pulpwood	.455 ± .041	101 ± 21	56.8 ± 3.7
Main stem	.485 ± .029	84 ± 13	55.7 ± 3.5
Branches	.433 ± .028	123 ± 21	59.9 ± 3.9
	BARK		
Total tree	0.349 ± 0.022	151 ± 15	53.3 ± 2.3
Saw log	.398 ± .037	117 ± 26	53.4 ± 3.2
Pulpwood	.316 ± .066	183 ± 57	53.5 ± 2.7
Main stem	.390 ± .035	121 ± 26	53.4 ± 3.3
Branches	.288 ± .016	195 ± 18	52.9 ± 1.8
	WOOD AND BARK		
Total tree	0.457 ± 0.020	96 ± 16	55.8 ± 2.9
Saw log	.478 ± .027	84 ± 10	54.5 ± 3.5
Pulpwood	.440 ± .041	110 ± 23	56.4 ± 3.3
Main stem	.475 ± .026	88 ± 12	55.3 ± 3.2
Branches	.398 ± .023	140 ± 17	58.3 ± 3.1

branches (0.433). Bark specific gravity was consistently lower than wood specific gravity, averaging 0.349 for the total tree, 0.390 for the main stem, and 0.288 for the branches. The specific gravity of the main stem bark approached that reported for longleaf pine (0.409) and was higher than that reported for loblolly, shortleaf, and slash pine. The branchbark specific gravity (0.288) was lower than that found for the four major species of southern pine.

Wood moisture content averaged 91 percent for the total tree, 84 percent for the main stem, and 123 percent for the branches (table 8). Wood moisture content was considerably higher for pulpwood (101 percent) than for saw logs (81 percent).

On a total-tree basis, bark moisture content averaged 151 percent, which was 60 percent higher than the corresponding value for wood (table 8). Bark moisture content was lower for saw logs (117 percent) than for pulpwood (183 percent) or branches (195 percent). The bark moisture contents reported here are all considerably higher (up to 100 percent higher) than those reported for other species of southern pine. These large differences are probably due to sand pine's considerably thinner bark and higher ratio of inner bark (which has an extremely high moisture content) to outer bark.

Green wood weight per cubic foot ranged from 54.7 pounds in saw logs to 59.9 pounds in branches and averaged 56.4 pounds in the total tree. Bark green weight per cubic foot was consistently lower than that of the wood (table 8), averaging about 53.4 pounds per cubic foot. Green weight of wood and bark per cubic foot of wood and bark averaged 55.8 pounds for the total tree, 55.3 pounds for the main stem, and 58.3 pounds for the branches.

PREDICTION EQUATIONS

Equations were developed to predict weights and volumes of the total tree and its components. Those used for predicting dry weight (Y) and green:dry weight ratio (Y_r) to 6- and 4-inch d.i.b. tops are presented in table 9. Similar equations for predicting cubic-foot volume (Y) and cubic-foot volume ratio (Y_r) are given in table 10. A ratio technique developed by Burkhart (1977) was used to avoid crossovers in which predicted values to a 6-inch top exceed values to a 4-inch top in the same tree. In this procedure, two equations are used to predict the weight or volume at any given top diameter: (1) a total stem volume of weight equation, and (2) an equation for estimating the ratio of merchantable stem volume or weight to total stem volume or weight for the specified top diameter. With these two equations, volume or weight can be obtained to any top diameter limit or between any two specific points on the stem simply by subtraction. In this study, we developed equations to predict the weight and volume ratios to a 6-inch d.i.b. top and a 4-inch d.i.b. top.

The equations presented in tables 9 and 10 for predicting wood, bark, and wood and bark to a 6- or 4-inch d.i.b. top predict only the volume or weight ratios of the merchantable stem and not the actual weight or volume. To find the weight or volume to these merchantable limits, the predicted ratio (Y_r) must be subtracted from the value 1 and then multiplied by the predicted total stem weight or volume. An example of application of this ratio technique is presented in the Appendix.

YIELD TABLES

For convenience to the users, the equations for total tree, stem to a 3-inch d.o.b. top, and crown in tables 9 and 10 were used to develop weight and volume tables; they are presented in the Appendix (tables 11–21). Other equations in tables 9 and 10 can be used to construct tables as needed, or they can be requested from the author.

Trees with the same d.b.h. and total height can vary considerably in weight and volume because of differences in crown size, moisture content, specific gravity, and taper. The yield tables presented in the Appendix should not be used indiscriminately over the range of sand pine without testing. Rather, they should be applied only to trees in natural stands which are similar in age, taper rate, and wood properties.

Table 9.—Regression equations for estimating green and dry weights and weight ratios of the aboveground biomass of Choctawhatchee sand pine trees and tree components with d.b.h. and total height as independent variables

Weight (Y)	Regression equation	Coefficient of determination (R^2)	Standard error $(S_{y \cdot x})^2$
Total tree (including needles):			
Green	$\text{Log}_{10}Y = -0.55650 + 0.95706\ \text{Log}_{10}D^2Th$	0.99	0.045
Dry	$\text{Log}_{10}Y = -0.91826 + 0.97593\ \text{Log}_{10}D^2Th$	.99	.043
Total tree (excluding needles):			
Green	$\text{Log}_{10}Y = -0.62122 + 0.96994\ \text{Log}_{10}D^2Th$	.99	.039
Dry	$\text{Log}_{10}Y = -0.97356 + 0.98720\ \text{Log}_{10}D^2Th$	.99	.047
Total tree—wood:			
Green	$\text{Log}_{10}Y = -0.79639 + 1.00201\ \text{Log}_{10}D^2Th$	.99	.041
Dry	$\text{Log}_{10}Y = -1.12844 + 1.01698\ \text{Log}_{10}D^2Th$	.99	.044
Total tree—bark:			
Green	$\text{Log}_{10}Y = -0.84088 + 0.77934\ \text{Log}_{10}D^2Th$	.96	.073
Dry	$\text{Log}_{10}Y = -1.16148 + 0.76005\ \text{Log}_{10}D^2Th$	.94	.088
Wood in total stem from stump to a 6-inch d.i.b. top:[3, 4]			
Green	$\text{Log}_{10}Y_r = 2.93777 - 3.62385\ \text{Log}_{10}D$	.85	.143
Dry	$\text{Log}_{10}Y_r = 3.01711 - 3.73405\ \text{Log}_{10}D$	.84	.156
Bark in total stem from stump to a 6-inch d.i.b. top:[3, 4]			
Green	$\text{Log}_{10}Y_r = 2.51837 - 3.15915\ \text{Log}_{10}D$	.87	.113
Dry	$\text{Log}_{10}Y_r = 2.51422 - 3.23465\ \text{Log}_{10}D$	.81	.148
Wood and bark in total stem from stump to a 6-inch d.i.b. top:[3, 4]			
Green	$\text{Log}_{10}Y_r = 2.90335 - 3.58539\ \text{Log}_{10}D$	.86	.139
Dry	$\text{Log}_{10}Y_r = 2.98467 - 3.70246\ \text{Log}_{10}D$	.84	.154
Wood in total stem from stump to a 4-inch d.i.b. top:[4]			
Green	$\text{Log}_{10}Y_r = 1.87940 - 3.58590\ \text{Log}_{10}D$	.94	.162
Dry	$\text{Log}_{10}Y_r = 1.97120 - 3.78576\ \text{Log}_{10}D$	.92	.211
Bark in total stem from stump to a 4-inch d.i.b. top:[4]			
Green	$\text{Log}_{10}Y_r = 1.52148 - 3.14421\ \text{Log}_{10}D$	.92	.169
Dry	$\text{Log}_{10}Y_r = 1.05411 - 2.86826\ \text{Log}_{10}D$	.73	.320
Wood and bark in total stem from stump to a 4-inch d.i.b. top:[4]			
Green	$\text{Log}_{10}Y_r = 1.84122 - 3.53864\ \text{Log}_{10}D$	.94	.158
Dry	$\text{Log}_{10}Y_r = 1.91231 - 3.72593\ \text{Log}_{10}D$	.96	.208
Wood in total stem from stump to a 3-inch d.o.b. top:			
Green	$\text{Log}_{10}Y = -1.08343 + 1.05588\ \text{Log}_{10}D^2Th$	.98	.052
Dry	$\text{Log}_{10}Y = -1.37915 + 1.06463\ \text{Log}_{10}D^2Th$	.98	.053
Bark in total stem from stump to a 3-inch d.o.b. top:			
Green	$\text{Log}_{10}Y = -1.20771 + 0.81960\ \text{Log}_{10}D^2Th$	.96	.069
Dry	$\text{Log}_{10}Y = -1.33809 + 0.76003\ \text{Log}_{10}D^2Th$	.94	.090
Wood and bark in total stem from stump to a 3-inch d.o.b. top:			
Green	$\text{Log}_{10}Y = -0.94689 + 1.03056\ \text{Log}_{10}D^2Th$	.99	.046
Dry	$\text{Log}_{10}Y = -1.23518 + 1.03557\ \text{Log}_{10}D^2Th$	.99	.046
Crown weight (including branchwood, branchbark, and needles):			
Green	$\text{Log}_{10}Y = -0.69292 + 0.81995\ \text{Log}_{10}D^2Th$	.86	.157
Dry	$\text{Log}_{10}Y = -1.13105 + 0.83740\ \text{Log}_{10}D^2Th$	.84	.165
Needles:			
Green	$\text{Log}_{10}Y = -1.41056 + 0.79520\ \text{Log}_{10}D^2Th$	.72	.233
Dry	$\text{Log}_{10}Y = -1.86151 + 0.80988\ \text{Log}_{10}D^2Th$	.72	.235
Wood in live branch material:			
Green	$\text{Log}_{10}Y = -1.03397 + 0.86048\ \text{Log}_{10}D^2Th$	.87	.153
Dry	$\text{Log}_{10}Y = -1.41556 + 0.87041\ \text{Log}_{10}D^2Th$	.86	.165
Bark in live branch material:			
Green	$\text{Log}_{10}Y = -1.12593 + 0.74215\ \text{Log}_{10}D^2Th$	.81	.166
Dry	$\text{Log}_{10}Y = -1.68595 + 0.76767\ \text{Log}_{10}D^2Th$	.82	.171
Wood and bark in live branch material:			
Green	$\text{Log}_{10}Y = -0.81148 + 0.83105\ \text{Log}_{10}D^2Th$	.86	.154
Dry	$\text{Log}_{10}Y = -1.25295 + 0.85039\ \text{Log}_{10}D^2Th$	.85	.164
Wood and bark in dead branch material:			
Green	—	—	—
Dry	$\text{Log}_{10}Y = -3.26819 + 1.17798\ \text{Log}_{10}D^2Th$	.79	.282

$\text{Log}_{10}Y = b_0 + b_1\ \text{Log}_{10}D^2Th$

where:

Y = weight of tree or component in pounds,
D = d.b.h. in inches,
Th = total height in feet

$\text{Log}_{10}Y_r = b_0 + b_1\ \text{Log}_{10}D$

where

$$Y_r = \frac{\text{Total stem weight} - \text{weight to specified d.i.b. top}}{\text{Total stem weight}}$$

D = d.b.h. in inches

[2] Standard error of estimate in Log_{10} form.

[3] Regression equations based on 24 trees 8 to 14 inches d.b.h.

[4] Weight to specified d.i.b. top can be computed using ratio values (Y_r) developed by these equations as follows:

Weight to specified d.i.b. top = $(1 - Y_r)$(total stem weight to 3-inch d.o.b. top)

Table 10.—Regression equations for estimating green cubic-foot and volume ratios of aboveground biomass of Choctawhatchee sand pine trees and tree components with d.b.h. and total height as independent variables

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error ($S_{y \cdot x}$)[2]
Total tree:			
Wood	$\text{Log}_{10}Y \quad -2.63695 + 1.02742\ \text{Log}_{10}D^2Th$	0.99	0.036
Bark	$\text{Log}_{10}Y = -2.52437 + 0.76732\ \text{Log}_{10}D^2Th$	.96	.076
Wood & bark	$\text{Log}_{10}Y = -2.43029 + 0.98764\ \text{Log}_{10}D^2Th$	.99	.032
Total stem to a 6-inch top:[3,4]			
Wood	$\text{Log}_{10}Y_r = 3.00835 - 3.70252\ \text{Log}_{10}D$	.86	.143
Bark	$\text{Log}_{10}Y_r = 2.52777 - 3.19292\ \text{Log}_{10}D$	.86	.123
Wood & bark	$\text{Log}_{10}Y_r = 2.97064 - 3.66251\ \text{Log}_{10}D$	.86	.140
Total stem to a 4-inch top:[3,4]			
Wood	$\text{Log}_{10}Y_r = 1.97174 - 3.72042\ \text{Log}_{10}D$	.93	.191
Bark	$\text{Log}_{10}Y_r = 1.45182 - 3.11971\ \text{Log}_{10}D$	.90	.185
Wood & bark	$\text{Log}_{10}Y_r = 1.91809 - 3.65827\ \text{Log}_{10}D$	.93	.183
Total stem to a 3-inch top:			
Wood	$\text{Log}_{10}Y = -2.92462 + 1.08298\ \text{Log}_{10}D^2Th$	.99	.052
Bark	$\text{Log}_{10}Y = -2.83818 + 0.79252\ \text{Log}_{10}D^2Th$	.97	.066
Wood & bark	$\text{Log}_{10}Y = -2.75688 + 1.04968\ \text{Log}_{10}D^2Th$	.99	.044
Live branch material:			
Wood	$\text{Log}_{10}Y = -2.83057 + 0.86608\ \text{Log}_{10}D^2Th$	.88	.151
Bark	$\text{Log}_{10}Y = -2.86248 + 0.74598\ \text{Log}_{10}D^2Th$	.81	.167
Wood & bark	$\text{Log}_{10}Y = -2.58501 + 0.83384\ \text{Log}_{10}D^2Th$	.87	.154
Dead branch material:			
Wood & bark	$\text{Log}_{10}Y = -4.72271 + 1.18320\ \text{Log}_{10}D^2Th$	.81	.271

[1] $\text{Log}_{10}Y = b_0 + b_1\ \text{Log}_{10}D^2Th$

where:

Y = cubic feet of tree or component,
D = d.b.h. in inches,
Th = total height in feet.

$\text{Log}_{10}Y_r = b_0 + b_1\ \text{Log}_{10}D$

where:

$$Y_r = \frac{\text{Total stem volume} - \text{volume to specified d.i.b. top}}{\text{Total stem volume}}$$

D = d.b.h. in inches.

[2] Standard error of estimate in Log_{10} form.

[3] Regression equations based on 24 trees 8 to 14 inches d.b.h.

[4] Cubic-foot volume to a specified d.i.b. top can be computed using ratio values (Y_r) as follows:

Volume to specified d.i.b. top = 1 − (Y_r) (total stem volume to 3-inch d.o.b. top).

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APPENDIX

ILLUSTRATION OF THE RATIO TECHNIQUE

Suppose you have a tree with a d.b.h. of 9.8 inches and a total height of 58 feet and you wish to compute the cubic-foot volume to a 4-inch top. First select the appropriate cubic-foot volume equation from table 10 for predicting total stem volume to a 3-inch top and substitute the tree dimensions:

$$\begin{aligned} \mathrm{Log}_{10}(Y) &= -2.75688 + 1.04968\ \mathrm{Log}_{10}(D^2(Th)) \\ &= -2.75688 + 1.04968\ \mathrm{Log}_{10}(9.8^2(58)) \\ &= 14.97\ \text{ft}^3 \text{ in total stem.} \end{aligned}$$

Cubic-foot volume to a 4-inch top (d.i.b.) is computed by substituting into the appropriate volume ratio (Y_r) equation in table 10. In this case, since we wish to predict volume of wood and bark to a 4-inch top, we would use the following equation:

$$\begin{aligned} \mathrm{Log}_{10}(Y_r) &= 1.91809 - 3.65827\ \mathrm{Log}_{10}(D) \\ &= 1.91809 - 3.65827\ \mathrm{Log}_{10}(9.8) \\ &= 0.01958. \end{aligned}$$

The ratio computed above is the proportion of wood in the main stem between the 4-inch (d.i.b.) and the 3-inch (d.o.b.) top. To compute the actual weight or volume to a 4-inch top, the above ratio must be subtracted from 1 and the resultant value multiplied by the previously computed total stem value as follows:

Volume to a 4-inch top

$$\begin{aligned} &= (1 - Y_r)\ (\text{Total stem volume to 3-inch top}) \\ &= (1 - 0.01958)\ (14.97\ \text{ft}^3) \\ &= 14.68\ \text{ft}^3 \end{aligned}$$

Table 11.—Predicted weight of total tree (wood, bark, and needles) above ground for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	69	102	135	167	198	
5	106	157	206	256	304	
6	151	222	293	362	431	500
7	202	298	393	487	579	671
8	261	385	508	628	748	867
9	328	483	636	787	937	1,086
10		591	778	963	1,147	1,329
11		709	934	1,156	1,376	1,595
12		837	1,103	1,365	1,626	1,884
13			1,285	1,591	1,895	2,196
14			1,481	1,834	2,183	2,530
15					2,492	2,888
	DRY[4]					
4	34	50	66	82	98	
5	52	77	102	127	152	
6	74	110	146	181	217	252
7	100	149	197	245	293	340
8	130	193	256	318	380	442
9	164	243	322	400	478	556
10		299	395	492	587	683
11		360	476	592	708	822
12		426	564	702	838	975
13			660	820	980	1,139
14			763	948	1,133	1,317
15					1,296	1,507

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\mathrm{Log}_{10}Y = -0.55650 + 0.95706\ \mathrm{Log}_{10}D^2Th$.

[4] $\mathrm{Log}_{10}Y = -0.91826 + 0.97593\ \mathrm{Log}_{10}D^2Th$.

Table 12.—Predicted weight of total tree (wood and bark) excluding needles for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	64	95	126	156	186	
5	99	147	194	241	288	
6	141	209	276	344	410	476
7	191	282	373	464	553	642
8	246	366	484	601	717	832
9	310	460	608	754	901	1,046
10		564	746	926	1,105	1,283
11		678	897	1,114	1,329	1,544
12		803	1,062	1,318	1,574	1,828
13			1,241	1,540	1,838	2,134
14			1,432	1,778	2,122	2,464
15					2,426	2,818
	DRY[4]					
4	32	47	63	78	93	
5	49	73	97	121	145	
6	70	105	139	174	208	242
7	95	142	189	236	282	328
8	124	185	246	307	367	428
9	157	234	310	387	463	540
10		288	382	477	570	664
11		347	461	575	689	802
12		412	548	683	818	952
13			642	800	958	1,115
14			743	926	1,109	1,291
15					1,270	1,479

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}Y = -0.62122 + 0.96994\ \text{Log}_{10}D^2Th$.

[4] $\text{Log}_{10}Y = -0.97356 + 0.98720\ \text{Log}_{10}D^2Th$.

Table 13.—Predicted weight of all aboveground wood excluding bark for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	52	78	104	130	156	
5	81	122	162	203	243	
6	117	175	234	292	351	409
7	159	238	318	398	477	557
8	208	312	416	520	624	728
9	263	394	526	658	790	922
10		487	650	813	976	1,139
11		590	787	984	1,181	1,378
12		702	937	1,171	1,406	1,641
13			1,100	1,375	1,651	1,927
14			1,276	1,595	1,915	2,235
15					2,199	2,566
	DRY[4]					
4	26	40	53	67	80	
5	41	62	84	105	126	
6	60	90	121	152	183	214
7	82	124	166	208	250	293
8	108	162	218	273	329	384
9	137	206	277	347	418	489
10		256	343	430	517	605
11		310	416	522	628	735
12		370	496	623	750	877
13			584	733	882	1,032
14			679	852	1,026	1,200
15					1,180	1,381

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\mathrm{Log}_{10}Y = -0.79639 + 1.00201\ \mathrm{Log}_{10}D^2Th$.

[4] $\mathrm{Log}_{10}Y = -1.12844 + 1.01698\ \mathrm{Log}_{10}D^2Th$.

Table 14.—Predicted weight of wood and bark in main stem to a 3-inch d.o.b. top for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	43	66	88	111	134	
5	68	104	140	176	212	
6	100	151	203	256	309	362
7	137	208	279	351	424	497
8	180	273	368	463	558	655
9	229	348	469	590	712	834
10		433	582	733	885	1,037
11		527	709	892	1,077	1,262
12		631	848	1,067	1,288	1,510
13			1,000	1,259	1,519	1,781
14			1,165	1,467	1,770	2,074
15					2,040	2,391
	DRY[4]					
4	23	35	47	59	71	84
5	36	55	74	94	113	133
6	53	80	109	137	165	194
7	73	111	149	188	227	267
8	96	146	197	248	300	352
9	123	187	251	317	383	449
10		232	313	394	476	558
11		283	381	480	580	680
12		339	456	575	694	814
13			538	678	819	961
14			628	791	955	1,120
15					1,102	1,292

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}Y = -0.94689 + 1.03056\ \text{Log}_{10}D^2Th$.

[4] $\text{Log}_{10}Y = -1.23518 + 1.03557\ \text{Log}_{10}D^2Th$.

Table 15.—Predicted weight of wood excluding bark in main stem to a 3-inch d.o.b. top for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	36	56	76	96	116	
5	58	90	121	154	186	
6	86	132	178	226	274	322
7	119	182	247	313	379	446
8	158	242	328	415	503	591
9	202	310	420	532	645	758
10		387	525	664	805	947
11		474	642	812	985	1,159
12		569	771	976	1,183	1,392
13			913	1,156	1,401	1,649
14			1,068	1,352	1,638	1,928
15					1,895	2,230
	DRY[4]					
4	19	30	41	52	62	
5	31	48	65	83	100	
6	46	71	96	122	148	175
7	64	98	134	170	206	242
8	85	131	178	225	273	322
9	109	168	228	289	351	414
10		210	286	362	440	518
11		258	350	444	539	635
12		310	421	534	648	764
13			499	633	769	906
14			585	741	900	1,061
15					1,043	1,229

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\mathrm{Log}_{10}Y = -1.08343 + 1.05588\ \mathrm{Log}_{10}D^2Th$.

[4] $\mathrm{Log}_{10}Y = -1.37915 + 1.06463\ \mathrm{Log}_{10}D^2Th$.

Table 16.—Predicted weight of crown material (branchwood, branchbark, and needles) in Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
			Pounds			
			GREEN[3]			
4	23	32	41	49	57	
5	33	46	58	70	82	
6	45	62	79	95	110	125
7	58	80	102	122	142	161
8	72	100	126	152	176	200
9	87	121	153	184	214	243
10		144	182	219	254	288
11		168	213	256	297	337
12		194	246	295	343	389
13			280	336	391	443
14			316	380	441	501
15					494	561
			DRY[4]			
4	9	13	17	20	23	
5	14	19	24	29	34	
6	18	26	33	39	46	52
7	24	33	42	51	59	68
8	30	42	53	64	74	84
9	36	51	64	78	90	103
10		60	77	93	108	123
11		71	90	109	126	144
12		82	104	126	146	167
13			119	144	167	190
14			135	163	189	216
15					213	242

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[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}Y = -0.69292 + 0.81995\ \text{Log}_{10}D^2Th$.

[4] $\text{Log}_{10}Y = -1.13105 + 0.83740\ \text{Log}_{10}D^2Th$.

Table 17.—Predicted weight of wood and bark in branches of Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
			Pounds			
			GREEN[3]			
4	19	26	33	40	46	
5	27	38	48	58	67	
6	37	51	65	78	91	104
7	47	66	84	101	118	134
8	59	83	105	126	147	167
9	72	100	128	154	179	203
10		120	152	183	213	242
11		140	178	214	250	284
12		162	206	248	288	228
13			235	283	329	374
14			266	320	373	424
15					418	475
			DRY[1]			
4	6	11	14	16	19	
5	11	16	20	24	28	
6	15	21	27	33	38	44
7	20	28	35	43	50	57
8	24	35	44	53	62	71
9	30	42	54	65	76	87
10		51	65	78	91	104
11		60	76	92	107	122
12		69	88	106	124	142
13			101	122	142	162
14			114	138	161	184
15					182	207

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}Y = -0.81148 + 0.83105\ \text{Log}_{10}D^2Th$.

[4] $\text{Log}_{10}Y = -1.25295 + 0.85039\ \text{Log}_{10}D^2Th$.

Table 18.—Predicted weight of branchwood in Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Pounds					
	GREEN[3]					
4	13	19	24	29	34	
5	19	26	35	43	50	
6	27	38	48	58	68	78
7	35	49	63	76	89	102
8	44	62	79	96	112	128
9	53	76	97	117	138	157
10		91	116	141	165	188
11		107	137	166	194	222
12		124	159	193	226	258
13			183	221	259	296
14			206	251	294	336
15					331	378
	DRY[4]					
4	6	8	11	13	15	
5	9	12	16	19	22	
6	12	17	22	26	31	35
7	15	22	28	34	40	46
8	19	28	36	43	51	58
9	24	34	44	53	62	71
10		41	52	64	75	85
11		48	62	75	88	101
12		56	72	88	103	117
13			83	101	118	135
14			94	114	134	153
15					151	173

[1] Blocked-in area indicates range of data.
[2] Includes 1-foot stump allowance.
[3] $\text{Log}_{10}Y = -1.03397 + 0.86048\ \text{Log}_{10}D^2Th$.
[4] $\text{Log}_{10}Y = -1.41556 + 0.87041\ \text{Log}_{10}D^2Th$.

Table 19.—Predicted green volume of wood and bark of the total tree for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
			Cubic feet			
			WOOD AND BARK[3]			
4	1.1	1.6	2.2	2.7	3.3	
5	1.7	2.6	3.4	4.2	5.1	
6	2.5	3.7	4.9	6.1	7.3	8.5
7	3.3	5.0	6.6	8.3	9.9	11.5
8	4.4	6.5	8.6	10.8	12.9	15.0
9	5.5	8.2	10.9	13.6	16.2	18.9
10		10.1	13.4	16.7	20.0	23.3
11		12.2	16.2	20.2	24.2	28.1
12		14.5	19.2	24.0	28.7	33.4
13			22.5	28.1	33.6	39.1
14			26.1	32.5	38.9	45.3
15				37.2	44.6	51.9
			WOOD[4]			
4	0.9	1.3	1.8	2.2	2.7	
5	1.4	2.1	2.8	3.5	4.2	
6	2.0	3.0	4.1	5.1	6.2	7.2
7	2.7	4.1	5.6	7.0	8.4	9.9
8	3.6	5.4	7.3	9.2	11.1	13.0
9	4.6	6.9	9.3	11.7	14.2	16.6
10		8.6	11.6	14.6	17.6	20.6
11		10.5	14.1	17.7	21.4	25.0
12		12.5	16.9	21.2	25.6	29.9
13			19.9	25.0	30.1	35.3
14			23.1	29.1	35.1	41.1
15				33.5	40.4	47.4

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\mathrm{Log}_{10}Y = -2.43029 + 0.98764\ \mathrm{Log}_{10}D^2Th$.

[4] $\mathrm{Log}_{10}Y = -2.63695 + 1.02742\ \mathrm{Log}_{10}D^2Th$.

Table 20.—Predicted green volume of wood and bark in the main stem to a 3-inch d.o.b. top for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	……………… *Cubic feet* ………………					
	WOOD AND BARK[3]					
4	0.8	1.1	1.5	2.0	2.4	
5	1.2	1.8	2.5	3.1	3.8	
6	1.8	2.7	3.6	4.6	5.5	6.5
7	2.4	3.7	5.0	6.3	7.6	9.0
8	3.2	4.9	6.6	8.4	10.1	11.9
9	4.1	6.3	8.5	10.7	13.0	15.2
10		7.8	10.6	13.4	16.2	19.0
11		9.6	12.9	16.3	19.8	23.2
12		11.5	15.5	19.6	23.7	27.9
13			18.3	23.2	28.1	33.0
14			21.4	27.1	32.8	38.6
15				31.3	37.9	44.6
	WOOD[4]					
4	0.6	1.0	1.3	1.7	2.0	
5	1.0	1.6	2.1	2.7	3.3	
6	1.5	2.3	3.1	4.0	4.9	5.7
7	2.1	3.2	4.4	5.6	6.8	8.0
8	2.8	4.3	5.9	7.4	9.1	10.7
9	3.6	5.5	7.5	9.6	11.7	13.8
10		6.9	9.5	12.1	14.7	17.4
11		8.5	11.6	14.8	18.1	21.3
12		10.3	14.1	17.9	21.8	25.8
13			16.7	21.3	25.9	30.6
14			19.6	25.0	30.4	36.0
15				29.0	35.4	41.8

---

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\mathrm{Log}_{10}Y = -2.75688 + 1.04968\ \mathrm{Log}_{10}D^2Th$.

[4] $\mathrm{Log}_{10}Y = -2.92462 + 1.08298\ \mathrm{Log}_{10}D^2Th$.

Table 21.—Predicted green volume of wood and bark in branches for Choctawhatchee sand pine trees 4 to 14 inches d.b.h.[1]

D.b.h. (inches)	Total-tree height[2] (feet)					
	20	30	40	50	60	70
	Cubic feet					
	WOOD AND BARK[3]					
4	0.3	0.4	0.6	0.7	0.8	
5	0.5	0.6	0.8	1.0	1.2	
6	0.6	0.9	1.1	1.4	1.6	1.8
7	0.8	1.1	1.4	1.7	2.0	2.3
8	1.1	1.4	1.8	2.2	2.5	2.9
9	1.2	1.7	2.2	2.6	3.1	3.5
10		2.1	2.6	3.2	3.7	4.2
11		2.4	3.1	3.7	4.3	4.9
12		2.8	3.6	4.3	5.0	5.7
13			4.1	4.9	5.7	6.5
14			4.6	5.5	6.4	7.3
15				6.2	7.2	8.2
	WOOD[4]					
4	0.2	0.3	0.4	0.5	0.6	
5	0.3	0.5	0.6	0.7	0.8	
6	0.4	0.6	0.8	1.0	1.1	1.3
7	0.6	0.8	1.0	1.3	1.5	1.7
8	0.7	1.0	1.3	1.6	1.9	2.2
9	0.9	1.3	1.6	2.0	2.3	2.6
10		1.5	2.0	2.4	2.8	3.2
11		1.8	2.3	2.8	3.3	3.7
12		2.1	2.7	3.2	3.8	4.3
13			3.1	3.8	4.4	5.0
14			3.5	4.2	5.0	5.7
15				4.8	5.6	6.4

[1] Blocked-in area indicates range of data.

[2] Includes 1-foot stump allowance.

[3] $\text{Log}_{10}Y = -2.58501 + 0.83384\ \text{Log}_{10}D^2Th$.

[4] $\text{Log}_{10}Y = -2.83057 + 0.86608\ \text{Log}_{10}D^2Th$.

Taras, Michael A.
1980. Aboveground biomass of Choctawhatchee sand pine in northwest Florida. USDA For. Serv., Res. Pap. SE-210, 00 p. Southeast. For. Exp. Stn., Asheville, N.C.

Choctawhatchee sand pine trees 4 to 14 inches d.b.h. were selected from a natural, uneven-aged stand in northwest Florida to determine the weight and volume of aboveground biomass. On the average, 85 percent of the green weight of the total tree was wood, 11 percent bark, and 4 percent needles. The average tree sampled had 82 percent of its wood in the stem and 18 percent in the crown. Specific gravity, moisture content, and green weight per cubic foot are presented for the total tree and its components. Tables developed from regression equations predict weight and cubic-foot volume of the total tree and its components by d.b.h. and total height classes.

KEYWORDS: *Pinus clausa* var. *immuginata* Ward, weight, volume, equations, component proportions.

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Growth and Yield in Natural Stands of Slash Pine and Suggested Management Alternatives

by Frank A. Bennett

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Growth and Yield in Natural Stands of Slash Pine and Suggested Management Alternatives

by
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ABSTRACT.—Yields are presented by stand age, site index, and stand basal area at the beginning of a growth period. Differences between these yields and those projected 20 and 50 years ago are explained partly by changing definitions of normal or full stocking and partly by changes in forest management. If only pulpwood harvesting is envisioned, fairly high stocking is needed to get full production from the site. To produce sawtimber and veneer in a 35-year rotation, however, stocking must be considerably lower. For longer sawtimber-veneer rotations, heavier stocking is required to maximize yield.

Keywords: *Pinus elliottii*, stand density, stocking, growth projections, yield tables.

In 1929 the U.S. Department of Agriculture issued Miscellaneous Publication 50 (MP-50), which contained yields for unthinned natural stands of slash pine (*Pinus elliottii* Engelm. var. *elliottii*), and other southern pines, with "normal" or full stocking. In 1960, Schumacher and Coile published yields for unthinned, "well-stocked" stands of slash and other southern pines. In 1970, I published variable-density yield tables and projected yields for thinned stands of natural slash pine (Bennett 1970). I also published yields for unthinned old-field slash pine plantations (Bennett and Clutter 1968).

This array of information might seem to preclude any need for additional reports on yields for this species, especially for natural stands. However, there are no published estimates of the effects of density on yields in unthinned natural stands, or of the effects of thinning on growth in natural stands. And the published effect of density on board-foot yield is contradictory—positive in natural stands and negative in plantations. Furthermore, the yield estimates in MP-50 and in Schumacher and Coile differ greatly. In this Paper, I—

- Describe and attempt to reconcile some of the differences between the earlier natural-stand data sets.
- Present yield tables by density classes for unthinned natural slash pine stands.
- Present data on periodic annual growth in thinned natural slash stands.
- Present modern slash pine yields for maximum stocking levels (normal yields).
- Explain the apparent contradictory effects of density on board-foot yields.
- Suggest some management alternatives based on growth and yield patterns observed in both natural stands and plantations.

CONFLICTING ESTIMATES

Differences between yields reported in MP-50 for "normal" stands and those in Schumacher and Coile for unthinned, well-stocked stands are quite large (table 1). MP-50 shows 13 to 133 percent more surviving trees per acre, 1 to 49 percent greater basal-area stocking, and 1 to 46 percent greater cubic-volume yield. Differences of this magnitude are of considerable practical significance.

Some of the differences can be explained by utilization standards. Schumacher and Coile include inside-bark volumes from stump to tip, but the appropriate MP-50 table for this comparison also includes stump volumes. Most of the differences in yield, however, arise from variations in the observed number of surviving trees per acre. The "normal" stands in MP-50 clearly are more heavily stocked than the "well-stocked" stands in Schumacher and Coile. For example, MP-50 shows 380 trees per acre as normal stock-

---

[1] Retired.

Table 1.—Slash pine stocking and cubic-yield inside bark from Miscellaneous Publication 50 (USDA 1929) and Schumacher and Coile (1960)

Age (years)	Data source[1]	Site index				
		60	70	80	90	100
		Number of trees/acre				
20	MP-50	2,035	1,445	1,090	835	625
	S&C	875	628	474	373	303
30	MP-50	1,140	820	610	470	365
	S&C	499	377	298	244	206
40	MP-50	710	500	380	295	225
	S&C	379	294	238	199	172
50	MP-50	550	390	295	220	175
	S&C	318	254	209	177	155
		Basal area in square feet/acre				
20	MP-50	143	146	148	149	150
	S&C	96	102	108	116	126
30	MP-50	152	156	158	159	160
	S&C	104	111	120	130	143
40	MP-50	155	159	161	163	164
	S&C	109	117	128	140	155
50	MP-50	157	161	163	165	166
	S&C	113	122	134	147	164
		Peeled cubic feet/acre				
20	MP-50	1,800	2,250	2,700	3,100	3,500
	S&C	1,360	1,770	2,240	2,810	3,480
30	MP-50	2,500	3,150	3,750	4,300	4,800
	S&C	1,870	2,390	3,000	3,720	4,580
40	MP-50	3,050	3,850	4,600	5,300	5,950
	S&C	2,200	2,800	3,500	4,320	5,350
50	MP-50	3,500	4,400	5,300	6,050	6,750
	S&C	2,390	3,100	3,880	4,780	5,920

[1] Data from Miscellaneous Publication 50 (MP-50) include trees 2 inches d.b.h. and above; total volumes inside bark are measured from groundline to treetop. Data from Schumacher and Coile (S&C) include all trees; total volumes inside bark are measured from stump height to tree top.

ing for site 80 at age 40. Schumacher and Coile show 238 trees per acre under comparable conditions. But I have measured stands at this age and site quality containing more than 700 stems per acre. In fact, in my study on natural stands of slash pine (Bennett 1970), the three stands I measured in the 60-year-age class contained an average of 445 stems per acre. These data illustrate that "normal stocking" and "well-stocked" are subjective terms impossible to calibrate in the forest. Today's intensive management practices require more precise information. Therefore, in this and other papers, I have reported yields for a wide range of ages, sites, and densities identified and accurately measured in the field.

SAMPLE DATA

The data used here came from 176 permanent, ¼-acre plots established in pure, natural slash pine stands in 1955–56. The sample area extended from Dooly County, Georgia, in the north to Hernando County, Florida, in the south and from the east coast of Florida and Georgia to

Santa Rosa County, Florida, in the west. Stands selected for sampling showed no evidence of thinning, severe burning, insect or disease damage, or collection of naval stores. Stocking ranged from 88 to 1,800 trees per acre, site index from 40 to 100, and age from 17 to 68 years. Average age was 31.4 years.

CUBIC YIELDS IN UNTHINNED STANDS

The diameters of all trees on each plot were measured to the nearest 0.1 inch. From a height-diameter curve constructed for each plot, a mean volume for each diameter class 5 inches and above was calculated from an equation from Cooper and Olson (1958):

$$\text{cubic-foot volume (outside bark)} = 0.002853D^2H - 0.976 \qquad (1)$$

where:

D = diameter at breast height in inches
H = total height in feet.

Plot volumes were established by applying diameter-class volumes to the observed diameter distributions and summing the results.

After expanding plot volumes to an acre basis, multivariate regression analysis was used to develop the following predictor:

$$\text{Log CFY} = 2.7058 - \frac{10.204}{\text{age}} + 0.87266\,(\text{log basal area}) - \frac{51.051}{\text{site index}} \qquad (2)$$

where log = common logarithm and CFY = cubic-foot yield (outside bark) per acre.

This simple model removed 94 percent of the variation in the logarithm of yield. The density variable accounted for 53 percent of the variation removed. The strong influence of density is reflected in yields as predicted by Equation (2) (table 2). For example, 100 square feet of basal-area stocking produce 83 percent more cubic yield than 50 square feet, and 125 square feet produce 56 percent more yield than 75 square feet. Since the average basal-area stocking in the slash-longleaf pine type is about 50 square feet, these figures demonstrate the urgent need to increase stocking on much of the acreage occupied by these species.

Note that, for a given basal-area density, 73 percent of the 50-year yield is produced by age 30 (table 2). The corresponding percentages for the data in MP-50 and Schumacher and Coile are 72 and 74, respectively. Yields estimated by Equation (2) for the basal-area stockings in MP-50 at age 30 range from 78 to 98 percent of the yields (outside bark) listed for normal stands. Estimates for Schumacher and Coile's densities at the same age range from 93 to 109 percent of the yields they list for well-stocked stands:

Site index	Estimated yield at age 30 as a percent of yield in—	
	(MP-50)	(Schumacher and Coile)[1]
60	78	93
70	86	106
80	88	107
90	94	109
100	98	103

[1] Outside-bark yields were estimated by applying ratios of inside-bark yields in MP-50 and Schumacher and Coile to the outside-bark yields in MP-50.

The differences between my estimates and those in MP-50 can be explained largely by differences in merchantability limits. MP-50 includes volumes in the entire stem from groundline to tip as well as those in trees 2 to 5 inches d.b.h. I report volumes from stump to a 4-inch top diameter outside bark, and I exclude yields in trees smaller than 5 inches d.b.h.

There is no easy explanation for my yields being larger than those of Schumacher and Coile. The difference would be even greater if they had not included upper-stem volumes and those in trees 1 to 5 inches d.b.h. No doubt, differences in the methods of construction of volume tables contribute to the discrepancies in yield. Schumacher and Coile's yields for slash pine are based on an adaptation of a loblolly pine volume table by MacKinney and Chaiken (1949).

The yields in table 2 cannot be directly compared on a maximum stocking basis with the yields in MP-50 or Schumacher and Coile. In order to produce such a comparison, the observed maximum numbers of surviving trees per acre in the study plots were smoothed by regression. The following equation was then entered with the predicted maximum number of trees, by age-site categories, to produce estimates of basal-area stocking:

Table 2.—Estimated per acre yields outside bark for unthinned, natural stands of slash pine[1]

Age (years)	50-year site index	Basal area (square feet)				
		50	75	100	125	150
		Cubic feet				
20	60	672	957	1,230	1,495	1,753
	70	889	1,267	1,628	1,978	2,319
	80	1,097	1,562	2,008	2,440	2,861
	90	1,291	1,840	2,364	2,873	3,368
	100	1,477	2,087	2,694	3,274	3,838
30	60	994	1,416	1,820	2,212	2,593
	70	1,315	1,874	2,408	2,926	3,431
	80	1,623	2,311	2,971	3,610	4,232
	90	1,910	2,721	3,498	4,250	4,983
	100	2,177	3,101	3,986	4,842	5,677
40	60	1,209	1,723	2,214	2,690	3,154
	70	1,600	2,279	2,929	3,559	4,173
	80	1,974	2,811	3,614	4,390	5,148
	90	2,323	3,310	4,254	5,169	6,061
	100	2,647	3,771	4,847	5,890	6,905
50	60	1,360	1,937	2,490	3,026	3,548
	70	1,799	2,563	3,295	4,003	4,693
	80	2,220	3,162	4,064	4,938	5,789
	90	2,613	3,722	4,785	5,813	6,816
	100	2,977	4,241	5,451	6,624	7,766

[1] Includes all trees 4.6 inches d.b.h. and larger to a 4-inch top d.o.b.

$$\text{Log basal area} = 1.52417 - \frac{6.74476}{\text{age}} - \frac{32.227}{\text{site}} + 0.45395\ \text{LogN} \qquad (3)$$

$$R^2 = 0.70$$

where log = common logarithm and N = number of trees per acre. Basal-area estimates from Equation (3) were then used in Equation (2) to estimate maximum cubic yields (table 3).

Except for site 60, the predicted maximum numbers of surviving trees per acre through age 40 are somewhat greater than the corresponding numbers in MP-50 and are, of course, well above those in Schumacher and Coile. For example, through age 40 the data on surviving trees in table 3 for sites 80 and above are from 25 to 100 percent greater than the corresponding data in MP-50. If volumes were computed with the same threshold diameter and utilization standards, it is evident that the yields in table 3 would be well above the MP-50 estimates, at least through age 40. This difference indicates that so-called normal stocking of one era will not necessarily apply in another.

The spread in basal-area yield within each site index class is much greater in table 3 than in MP-50 because of a much smaller spread in number of trees per acre in MP-50. Consequently, the effect of site on cubic yield as shown in table 3 is much greater than that shown in MP-50. For example, yields in MP-50 for site 70 are about 70 percent of the yields for site 100, whereas yields in table 3 for site 70 range from 49 to 56 percent of the yields for site 100. The effect of site on yield in table 3 would be reduced, of course, if volume for all trees 2 inches and above were included.

PERIODIC ANNUAL GROWTH IN THINNED STANDS

The 176 quarter-acre plots were established to evaluate growth and total yield for given residual densities in thinned stands. Accordingly, each plot was assigned a stocking density and, if

Table 3.—Per acre cubic-volume and basal-area yields outside bark for maximum stocking levels in unthinned, natural stands of slash pine

Age (years)	Site index														
	60			70			80			90			100		
	Trees	Yield[1]	Basal area	Trees	Yield[1]	Basal area	Trees	Yield[1]	Basal area	Trees	Yield[1]	Basal area	Trees	Yield[1]	Basal area
	No.	*Cubic feet*	*Square feet*	*No.*	*Cubic feet*	*Square feet*	*No.*	*Cubic feet*	*Square feet*	*No.*	*Cubic feet*	*Square feet*	*No.*	*Cubic feet*	*Square feet*
20	1,652	1,537	129	1,520	2,292	148	1,421	2,507	164	1,344	3,305	177	1,282	4,695	189
30	1,020	2,608	134	888	3,450	151	789	4,550	163	712	5,614	172	651	6,656	180
40	704	2,765	129	572	3,929	140	474	5,057	147	394	6,060	150	335	6,945	151
50	515	2,941	121	383	4,030	126	284	4,792	126						

[1] Includes all trees 4.6 inches d.b.h. and larger to a 4-inch top d.o.b.

required, was thinned to that level initially, and at 5-year intervals thereafter. Unfortunately, 94 plots were destroyed or inadvertently thinned during the first 5-year growth period. Our study design held basal area constant within site and forced a negative correlation between site index and number of trees per acre. Also, mortality in number of trees per acre was essentially the same on all sites. These results masked the effect of site on basal area and cubic-volume growth since tree sizes increased as site increased. However, remeasurement of 121 plots at the end of the second 5-year growth period permitted development of the following equations for predicted and projected yield and growth:

$$\mathrm{Ln}Y = 5.98812 - \frac{121.713}{S} - \frac{19.758}{A} + 0.89683\,\mathrm{Ln}B \qquad (4)$$

$$\mathrm{Ln}Y_2 = 5.98812 - \frac{121.713}{S} - \frac{19.758}{A_2} + 4.632\left(1 - \frac{A_1}{A_2}\right) + 0.89683(\mathrm{Ln}B_1)\left(\frac{A_1}{A_2}\right) \qquad (5)$$

$$\mathrm{Ln}B_2 = \mathrm{Ln}B_1\left(\frac{A_1}{A_2}\right) + 5.1649\left(1 - \frac{A_1}{A_2}\right) \qquad (6)$$

$$CFG = Y\left[\frac{19.758}{A^2} - 0.89683\,\frac{\mathrm{Ln}B}{A} + \frac{4.632}{A}\right] \qquad \text{(7)[2]}$$

$$BFY = 1236.12 - 186.16011(B) + 7.31406\,(\text{cubic-foot stocking}) \qquad \text{(8)[3]}$$

where:

Ln = natural logarithm
Y = cubic-foot yield
Y_2 = projected cubic-foot yield
S = 50-year site index
A = any given age
A_1 and A_2 = initial and terminal age
B = any given basal area
B_1 and B_2 = initial and terminal basal-area stocking
CFG = periodic annual cubic-foot growth rate
BFY = board-foot yield

Theoretically, Equation (7) does not estimate the volume that accrues over a year; rather, it gives an instantaneous growth rate applicable only at a specific age (table 4). Practically, however, estimates derived from this equation are good indicators of current annual increment, because the amount of change in cubic volume and basal-area stocking (independent variables in this equation) over the span of a year does not greatly alter the growth rate.

Slightly more accurate estimates of current annual growth can be obtained by using Equations (5) and (6) to project cubic volume and basal-area stockings at yearly intervals. From these stocking data, growth rate can be estimated at

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[2] Equation (7) was not published at the time the others in this group were, but it was developed at the time the others were.

[3] All equations were developed by Dr. J. L. Clutter, University of Georgia.

Table 4.—Instantaneous rates of cubic-foot growth per acre at specific ages in thinned, natural stands of slash pine, by site index and basal-area stocking

Age (years)	50-year site index	Basal area (square feet)				
		50	75	100	125	150
		Cubic feet				
	60	69	82	90	96	98
	70	92	109	121	128	131
20	80	114	136	150	159	163
	90	135	161	178	188	193
	100	155	184	204	215	221
	60	54	62	65	66	64
	70	72	82	87	88	86
30	80	89	102	108	110	107
	90	106	121	128	130	127
	100	121	139	147	149	145
	60	43	48	49	48	45
	70	58	64	66	65	60
40	80	72	80	82	80	75
	90	85	95	97	95	89
	100	97	108	111	109	102
	60	36	39	39	37	34
	70	48	52	53	50	45
50	80	59	65	65	62	56
	90	70	77	77	73	66
	100	81	88	89	84	76

yearly intervals and average growth rates can be computed. For example, the average of the growth rates at ages 20 and 21 would represent current annual growth for the 20th year.

Current annual increment of merchantable volume is greatest at age 20 and declines thereafter. As in unthinned stands, this increment is maximum in thinned stands at an early age (sometime prior to age 20) because it is a function of number of trees per acre. Consequently, ingrowth, diameter growth, and good height growth at young ages, produce early culmination of current and periodic annual increment of merchantable volume.

As with all growth patterns, added units of stocking contribute successively lower volumes of increment. Otherwise, culmination would never occur. The point of primary interest on managed stands is the amount of volume increase per increased unit of stocking. At the point of culmination of periodic annual growth, a large portion of the stocking contributes only a minor amount to the total production (table 5). On the basis of the data in table 5, attainment of the biological growth potential is financially unattractive, to say the least.

Although no equation for board-foot growth was developed in the analysis of the study data, an estimate of sawtimber growth can be derived from

Table 5.—Contributions of various stocking levels to total growth at the point of culmination in thinned, natural stands of slash pine

Age (years)	Basal-area stocking (square feet)						
	25	50	75	100	125	150	175
	Percent of total growth[1]						
20	48	70	83	91	97	99	100
30	59	81	93	98	100		
40	65	88	98	100			
50	69	91	100				

[1] These data hold, with very minor variations, for all sites

Table 6.—Periodic annual board-foot growth as developed from projected board-foot yields for thinned, natural stands of slash pine

Age (years)	50-year site index	Basal area (square feet)			
		50	75	100	125
		Board feet			
20	70	0	0	0	0
	80	0	0	0	0
	90	434	609	726	275
	100	576	783	912	1,138
30	70	43	208	0	0
	80	67	348	445	577
	90	290	489	585	680
	100	400	612	719	818
40	70	130	178	224	274
	80	236	284	339	388
	90	332	393	446	488
	100	418	489	551	591
50	70	113	146	173	209
	80	204	239	265	295
	90	279	326	355	380
	100	353	406	433	461

projected board-foot yields (table 6). Projected board-foot yields were obtained by applying Equation (8) to projected cubic volume and basal-area yields (Bennett 1970). Like cubic-volume growth, periodic annual board-foot growth is greatest at age 20. The very high growth rate on the best site at age 20 no doubt reflects heavy ingrowth. Site 60 is excluded from table 6 because it shows no sawtimber potential. Sites 70 and 80 show no board-foot production at age 20, even for low densities. Stands on these sites averaged 714 and 466 trees per acre at age 20, and thinnings did not occur until this age or later. Board-foot growth shows no culmination in relation to density except on site 90 at age 20 and on site 70 at age 30. The projected board-foot yields show essentially the same pattern. In contrast, board-foot yields in plantations culminate in relation to stocking on all sites at 200 to 300 trees per acre, but they do not culminate on any site in relation to age up to age 30. Light stockings in both plantations and natural stands permit rapid diameter growth and, of course, produce early and large board-foot yields. However, as age increases in both types of stands, more and more trees become sawtimber size, and board-foot yield then tends to increase as density increases. Once all trees reach sawtimber size, to use the perfect example, every time we add a cubic foot of growth we increase board-foot yield, and we know that cubic-foot growth and yield increase as density increases.

CHANGING CONDITIONS

Comparison of the new cubic yields for maximum stocking in table 3 with those from MP-50 and Schumacher and Coile in table 1 illustrates that "normal stocking" and "well stocked" are concepts that are strongly influenced by personal judgment. Although based on a sound biological principle, the concept of normal stocking is not useful in applied management because it is not definable in measureable parameters. Furthermore, it is not economically viable in a freely competitive market of diversified primary products, nor will it be as long as the free market dictates management. Even if defined in terms of products, the concept is not economically viable because there is a point beyond which the cost of carrying additional stocking exceeds the return from the added stocking.

If we grant that the yields published in 1929 for normal stocking represented the maximum for that era, then the data in table 3, especially for ages 20 and 30, demonstrate that optimum stocking of one period may not apply to subsequent stands produced under different conditions. A stand or forest type is a product of its history. The lack of management—indeed, the mismanagement and destructive practices of the late 1800's and early 1900's—must have been reflected, to some extent, in the normal yields of the 1920's. It is not surprising, therefore, that optimum stocking and yield patterns developed under a better level of management and fire protection are different from those presented in MP-50.

MANAGEMENT ALTERNATIVES

From the growth and yield patterns reported here for natural stands and those previously observed in slash pine plantations, we can determine stocking levels and rotation lengths that appear best for growing various products. Yield tables for both plantations and natural stands demonstrate that cubic yield is a function of number of trees per acre—as trees per acre increase, cubic yield increases. Tables of board-foot yields for natural stands also show that both these yields and periodic growth increase as density increases. Tables of board-foot yields for plantations, on the other hand, show that board-foot yields at age 35 and under are greatest in stands of 200 to 300 trees per acre. These growth and yield patterns suggest the following alternative management regimes for the two types of stands:

1. For pulpwood production on a 25- or 30-year rotation, a fairly heavily stocked stand is needed. Since the yield increase per unit of stocking will decline as stocking increases, the optimum stocking level will depend on overall management costs, including harvesting costs as influenced by tree size. For this reason, specific stand stockings are not suggested. The owner or manager can be guided by the fact that cubic production and harvesting costs increase with density and that densities beyond 600 trees per acre significantly reduce height growth.

2. For sawtimber and veneer production in a relatively short rotation (35 years), no more than 200 to 300 surviving trees per acre are needed to maximize yields. In plantations, the equivalent of a 10- by 10-foot or greater spacing should be used if total product yield is the primary concern. This assumes a survival percentage of 75 to 80. In natural stands, a precommercial thinning to this level of stocking at an early age (before age 5) would be required. Lightly stocked stands on good sites can be commercially thinned around age 20 to stimulate diameter growth without reducing sawtimber ingrowth in a short rotation.

3. For sawtimber and veneer production in rotations over 40 years, especially those 45 years and above, the stand should be started with several hundred surviving trees per acre, if near maximum volume production is desired. Such a level will permit two or more thinnings, with an accompanying increase in average tree quality and the heavier basal-area stocking necessary for optimum, or near optimum, board-foot and veneer yields in these long rotations.

As we have seen, board-foot yields in natural stands increase as basal-area density increases. This pattern develops when a majority of the trees reach sawtimber-size and it will continue until density causes mortality among sawtimber-size trees. It is easy to rationalize a positive correlation between board-food growth and density. As noted earlier, once all trees are of sawtimber size and quality, every cubic foot of growth, at least in the saw-log portion of the tree, is board-foot growth. Hence, heavier stocking is needed to maximize board-foot growth and yield in long rotations.

We should note again, however, that the density which maximizes product yield is not likely to optimize net return. The stocking level that will produce the greatest net return is influenced greatly by management costs, interest rates, taxes, etc., and these are not stable variables. When we consider further that the law of diminishing returns applies to stocking, it becomes difficult to specify an optimum density that will hold for a majority of owners. As with cubic production, the owner or manager must be guided by the fact that board-foot and veneer-stock production is positively correlated with density in long rotations, and that harvesting and manufacturing costs are markedly influenced by tree size.

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Yields are presented by stand age, site index, and stand basal area at the beginning of a growth period. Differences between these yields and those projected 20 and 50 years ago are explained partly by changing definitions of normal or full stocking and partly by changes in forest management. If only pulpwood harvesting is envisioned, fairly high stocking is needed to get full production from the site. To produce sawtimber and veneer in a 35-year rotation, however, stocking must be considerably lower. For longer sawtimber-veneer rotations, heavier stocking is required to maximize yield.

KEYWORDS: *Pinus elliottii*, stand density, stocking, growth projections, yield tables.

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Two-Stage Stratified Sampling with Regression to Assess Southern Pine Beetle Damage

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Two-Stage Stratified Sampling with Regression to Assess Southern Pine Beetle Damage

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Abstract.—A field test of two-stage stratified sampling with double sampling at the second stage is described. First-stage stratification was based on timber type and on a sketch map reconnaissance flight. Second-stage stratification was based on sketch mapping and aerial photo estimates of spot sizes. This same substratification variable was used as the independent variable in regression with dependent variables: number of red, fading, and green trees and total basal area as measured on the ground on 85 spots. Estimated totals for these variables based on regression had standard errors of estimates between 10 and 20 percent of the estimated totals. Regression estimates for some of the strata differed considerably from simple stratified-sampling estimates. Sketch mapping located only 29 percent of the spots found by photo interpretation in a heavily infested stratum.

Based on the field test, we recommend that all heavily infested strata be 100 percent photographed and all light-infested strata either be 100 percent sketch mapped or preferably also photographed 100 percent. Only highly trained interpreters and sketch mappers should be used, and they should spend extra effort at getting good estimates for the large spots which heavily influence the regression results. In addition, the interpreter should use only good-quality, high-magnification equipment.

Keywords: Stratification, pilot study, sketch mapping, aerial photographs, practical recommendations.

Some assessment of pine mortality due to southern pine beetles (SPB) is important in combating this pest and in salvaging timber killed by it. Obtaining information that is sufficiently reliable for statistical assessment is very expensive. Information is obtained primarily by aerial sketch mapping, which is inexpensive but unreliable. This Paper presents a useful statistical design for obtaining reliable information and describes a field test of that design.[2]

In aerial surveys, an observer in the airplane must sketch existing spots, estimate the number of trees in each spot, and assess the probable accuracy of his plotting of the location of each spot on his survey map. During 1 minute he must plot all spots in a 0.8- by 1.6-km area—about 260 ha.[3] The observer in a sketch map survey must be able to perform these procedures for up to 4 hours in a light aircraft flying close to the ground. In this procedure, accuracy obviously depends heavily on the skill of the observer. Aerial photography, an alternative to sketch mapping, is more expensive and takes more time, but it reduces the error if the interpreter is skilled and diligent.

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[1] Schreuder is currently Mathematical Statistician at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

[2] The design was originally described by H. T. Schreuder, W. H. Clerke, and P. J. Barry in 1977: A flexible three-stage sampling design with double sampling at the second stage in estimating southern pine beetle spot characteristics. Final Report, Expanded Southern Pine Beetle Research and Application Program.

[3] Aldrich, R. C., R. C. Heller, and W. F. Bailey. 1958. Observation limits for aerial sketch-mapping southern pine beetle damage in the Southern Appalachians. J. For. 56:200–202.

With sketch mapping or aerial photography, some observations must be made on the ground to adequately describe ground conditions. These observations are very expensive, so a sampling design that minimizes them is required. The sampling design must also allow for efficient estimates of the variable(s) of interest. In southern pine beetle surveys, we are usually interested in number of trees that have been killed by southern pine beetles on spots of various sizes and on an area as a whole.

Various multistage sampling designs have been used with either sketch mapping or aerial photography in conjunction with ground sampling (*see* footnote 2). Several of these designs emphasized the use of unbiased estimators obtained through the use of sampling with probability proportional to size (p.p.s. sampling) using the usual ratio estimator associated with this type of sampling. Stuart illustrated why stratified sampling may be superior to p.p.s. sampling in some cases.[4] Schreuder showed that stratified sampling with an appropriate estimator is superior to Poisson (or 3-P) sampling with the usual ratio-type estimator.[5] Application of stratified sampling guarantees that a fixed, desired percentage of the sample is allocated to each stratum of the population during any survey, while application of p.p.s. sampling only generates this size-based stratification on the average over a large number of surveys.

STUDY AREA

The area on which the survey design was demonstrated includes the Chattooga, Tallulah, and Brasstown Ranger Districts on the Chattahoochee National Forest in northeastern Georgia. The area is in the Southern Appalachian Mountains, and elevation ranges from 366 to 1,524 m. About half of the 296,588 ha within the district boundaries are privately owned. Both private and public lands were included in the survey.

Pine types occupy 30 percent of the forest area, oak-pine 20 percent, and oak-hickory 48 percent. The remainder is in miscellaneous nonpine types. Almost all of the pine is shortleaf (*Pinus echinata* Mill.).

SAMPLING

Since our interest was in southern pine beetle damage, our first step was to eliminate nonpine timber types. National topographic maps, county vegetation maps, Forest Service compartment maps, and a sketch map reconnaissance flight made just prior to sampling, provided the information for this step.

Next, we set up six major strata based on forest type, amount of beetle infestation, and geography:

1A & 1B.	Pine types containing many and large beetle spots—two strata called 1A and 1B were set up based on geography.
2.	Pine types containing fewer and smaller spots.
3A & 3B.	Pine-hardwood types lightly infested with beetles—two strata called 3A and 3B were set up based on geography.
4.	Pine-hardwood types very lightly infested with beetles.

In the terminology of this Paper, division of the area into primary strata is called the first stage. Boundaries for strata should be based on easily identifiable features such as forest types, roads, rivers, and so forth, because the acreage in each stratum must be estimated with good precision. Also, strata must be identifiable from the air or on aerial photographs.

In the second stage of the recommended sampling technique, strata must be subdivided into smaller subpopulations that are more homogeneous with respect to the variables of interest. To do this, substrata are set up on the basis of the number of red and fading trees estimated to be in each spot during aerial photo interpretation and sketch mapping. A total of 15 substrata representing spot sizes ranging from less than 10 to more than 250 trees were recognized (table 1).

Aerial photography and sketch mapping were completed in August, and sample spots were

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[4] Stuart, A. 1963. Some remarks on sampling with unequal probabilities. Stat. Method. 4:773–780.

[5] Schreuder, H. T. 1974. Two stratified sampling alternatives to 3-P sampling. *In* Monitoring forest environment through successive sampling. p. 55–58. Proc. State Univ. N. Y., Coll. Environ. Sci. and For., Syracuse.

Table 1.—Spot-size distribution based on aerial estimates and sample-size allocation by strata and substrata as determined from aerial photography or sketch mapping

Stratum (in hectares)	Substratum	Aerial information	Percent survey	Trees per spot	Spots observed on			False spots
					Photo	Sketch map	Ground	
1A	1	Photo	100	1–49	263		7	1
(17,440)	2	Photo	100	50–250	50		11	0
	3	Photo	100	> 250	6		6	0
Total					319		24	
1B	1	Photo/Sketch	100	1–7	231	28	5	1
(20,311)	2	Photo/Sketch	100	8–19	114	32	5	0
	3	Photo/Sketch	100	20–49	61	32	5	0
	4	Photo/Sketch	100	50–200	52	39	8	0
	5	Photo/Sketch	100	201–2,000	3	3	3	
Total					461	134	26	
2	1	Photo	88	1–10	36		5	1
(1,539)	2	Photo	88	11–35	34		7	0
Total					70		12	
3A	1	Sketch	50	1–15		38	6	0
(6,045)	2	Sketch	50	16–50		8	3	0
Total						46	9	
3B	1	Sketch	50	1–50		5	4	0
(16,121)								
4	1	Sketch	25	1–9		39	6	0
(87,692)	2	Sketch	25	10–150		38	7	0
Total						77	13	

visited by ground crews in September through November. Each attacked tree on sample spots containing less than 500 trees was examined, and its species, diameter at breast height, crown color, and beetle status were recorded. On spots containing more than 500 trees, one tree in five was examined. Eighty-eight spots were examined on the ground.

RESULTS AND DISCUSSION

The intent of the sampling design was to group spots similar in size in the same stratum and to select the large spots with high and small spots with low probability for ground cruising (table 1). For example, the six largest spots in 1A were selected with certainty, while the spots with 1 to 49 trees were selected with probability of 7/263 = 0.027. We wasted sampling effort in 3B where the small spots (1 to 50 trees) were selected with probability 0.80 for ground cruising. Stratum 3B should have been logically combined with either 3A or 4.

Three of the 88 places ground checked were falsely classified as "spots." Misclassification amounted to 14 percent in stratum 1A for spot size 1 to 49 and 20 percent in stratum 2 for spot size 1 to 10 (spot selection in 1B was done on the basis of sketch mapping information to implement ground sampling sooner).

Plotting variables of interest, as measured on the ground against number of red and fading trees estimated from the air, showed that the relationships were linear and that positive correlations were obtained in all cases only when substrata were ignored. We decided to combine all noncensused substrata in 1A and 1B in one regression but use a different regression for stratum 2. Regression estimation is not needed for totally enumerated substrata 3 in stratum 1A and 5 in 1B because for those substrata the estimates have no sampling error. For regression estimation, strata that were sketch mapped were combined. Substrata data were combined into one regression equation as explained in Cochran, sect. 7.7–7.9.[6]

To show the gain from using regression estimation for ground-measured variables, estimates were computed with and without regressions (table 2). It is evident that the regression estimates usually are more precise than the simple stratified-sampling estimates. In strata 1A and 1B, totals estimated by the two methods are similar, but the standard errors are consistently lower for the regression estimates. In strata 2, 3A, 3B, and 4, considerable differences in totals estimated by the two methods are evident. These differences are probably attributable to the unreliable estimation of number of red and fading trees for large spots by the sketch mapper. In stratum 2, the size of the one large spot was greatly underestimated. Apparently that spot expanded between the time of photography and the time of ground cruising.

Table 2.—Stratified-sampling and regression estimates plus standard errors (in parentheses) by strata and population for red and fading (R + F), red and fading green infested (TI), and total basal area of infested and killed trees (BA) in m^2

Variable	Type of estimate	Strata						
		1A	1B	2	3A	3B	4	Total
R+F	Stratified	9,566 (2,321)	11,234 (1,497)	3,083 (1,670)	3,075 (854)	147 (100)	18,244 (9,567)	45,350 (10,134)
R+F	Regression	10,057 (1,063)	11,357 (1,529)	4,723 (1,215)	2,506 (727)	417 (166)	13,453 (3,789)	42,513 (4,456)
TI	Stratified	3,302 (1,118)	5,127 (770)	3,667 (1,942)	2,114 (539)	44 (26)	21,212 (10,224)	35,469 (10,510)
TI	Regression	4,352 (516)	4,423 (741)	6,234 (1,343)	5,134 (1,852)	500 (218)	15,145 (5,998)	35,787 (6,487)
BA	Stratified	44.9 (78.9)	702.1 (84.0)	143.3 (60.6)	150.2 (35.4)	13.5 (10.1)	1,283.2 (711.7)	2,801.7 (724.4)
BA	Regression	535.2 (46.2)	695.3 (66.4)	200.8 (47.2)	173.3 (80.6)	28.0 (13.0)	900.6 (322.9)	2,532.9 (346.1)

Although stratum 4 was only lightly infested, the large size of the stratum and the detection of one large spot resulted in large estimated values of all parameters. Because the stratum was only 25 percent sketch mapped, the large spot represents a 25 percent sample of the large spots in this stratum, and the standard errors of estimates are very large. With 100 percent sketch mapping, the large spots could have been censused on the ground and standard errors of estimates would have been reduced dramatically.

In stratum 1B there was a higher correlation between ground variables and sketch-mapped estimates than with aerial photograph estimates. Apparently the sketch mapper did a better job than the photo interpreter on the one large spot included in the regression. In fact, regressions for strata 1A, 1B, and 2 would predict better if the interpreter had done a better job on the large spots.

The results for stratum 1B show that sketch mapping is not a useful technique in heavily infested strata. Only 29 percent of the spots identified on the photographs were plotted by the sketch mapper.

RECOMMENDATIONS

On the basis of experience gained from this survey, we feel we can make the following recommendations:

- The basic design is of considerable practical utility. For best results, however, photograph all heavily infested strata 100 percent and either photograph or sketch map all lightly infested ones 100 percent.
- Do not sketch map strata with heavy infestations. Only 29 percent of the spots identified on photographs were noted during sketch mapping in our heavily infested stratum.
- Use only highly trained interpreters and sketch mappers, and let interpreters use only good-quality, high-magnification equipment.

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[6] Cochran, W. G. 1963. Sampling techniques. 2d ed. 330 p. John Wiley and Sons, Inc., New York.

- Ground check as soon as possible after sketch mapping or photography. Photo interpretation should be done very quickly to minimize the timelag.
- Compare estimates by regression and simple stratified-sampling techniques.
- Sample large spots heavily because results there have the greatest influence on the least-squares regression results.
- Subsample large spots to be ground checked. A 5 percent sample with a minimum sample size of 100 trees should be adequate.

ESTIMATION THEORY

For simplicity we assume that all strata (k) are either 100 percent photographed or 100 percent sketch mapped and that the number of spots detected from the air is the true number of spots in each stratum. Although this assumption was not made in the text for estimation, we feel that in future applications of this design, 100 percent sketch mapping or photography should be used. We base our theory here on this assumption. We also assume that all substrata in a given stratum which are not 100 percent ground checked are included in the same regression. Substrata that are 100 percent ground checked have no measurement error and hence do not contribute to error. We will call our variable of interest, y. It may be total basal area, number of dead trees, number of trees attacked by SPB, or any other variable which requires ground measurement to be accurate. For convenience, we will talk about number of red and fading trees (as measured on the ground). Our independent variable, hopefully highly correlated with our variable of interest, is x. It may be any continuous variable measured or estimated from either photographs or sketch mapping. In our case, it is number of red and fading trees on SPB spots (as estimated from photographs or sketch mapping). When combining substrata in a single regression, we ignore in our notation what strata they come from. We also give estimation equations for individual strata which are often of interest. More general theory is given in Schreuder and others (*see* footnote 2), but we feel the theory presented here is simpler and adequate for practical purposes.

Our total estimated number of red and fading trees in the population is

$$\hat{Y} = \sum_{\ell=1}^{r} \hat{Y}_\ell + Y_c = \sum_{h=1}^{k} \hat{Y}_h \qquad (1)$$

where

r = number of regressions ($r \leq k$),

$\hat{Y}_\ell$ = estimated number of red and fading trees for substrata in regression ℓ,

Y_c = total number of red and fading trees in substrata that are 100 percent ground checked,

and

$\hat{Y}_h$ = estimated total for stratum h.

Then, the estimation number of red and fading trees for all substrata contained in regression ℓ is

$$\hat{Y}_\ell = N_\ell \hat{\bar{Y}}_\ell = N_\ell(a_\ell + b_\ell \bar{X}_\ell) \qquad (2)$$

with

$$\begin{aligned} b_\ell = & \sum_{j=1}^{s_\ell} \left(N_{\ell j}^2[1 - (n_{\ell j}/N_{\ell j})] / [n_{\ell j}(n_{\ell j} - 1)]\right) \\ & \times \sum_{i=1}^{n_{\ell j}} (Y_{\ell ji} - \bar{Y}_{\ell j})(X_{\ell ji} - \bar{X}_{\ell j}) \\ & \div \sum_{j=1}^{s_\ell} \left(N_{\ell j}^2[1 - (n_{\ell j}/N_{\ell j})] / [n_{\ell j}(n_{\ell j} - 1)]\right) \\ & \times \sum_{i=1}^{n_\ell} (X_{\ell ji} - \bar{X}_{\ell j})^2 \end{aligned} \qquad (3)$$

and

$$a_\ell = \bar{Y}_\ell - b_\ell \bar{X}_\ell . \qquad (4)$$

Here

N_ℓ = number of spots included in regression ℓ,

$\hat{\bar{Y}}_\ell = \sum_{j=1}^{s_\ell} (N_{\ell j}/N_\ell) \sum_{i=1}^{n_{\ell j}} Y_{\ell ji}/n_{\ell j}$ is the average number of red and fading trees per spot in regression ℓ,

$\bar{X}_\ell = \sum_{j=1}^{s_\ell} (N_{\ell j}/N_\ell) \sum_{i=1}^{n_{\ell j}} X_{\ell ji}/n_{\ell j}$ is the average number of red and fading trees per spot in regression ℓ estimated from the air,

s_ℓ = number of substrata included in regression ℓ.

$N_{\ell j}$ = number of spots in substratum j of regression ℓ,

$n_{\ell j}$ = number of spots in substratum j of regression ℓ sampled on the ground,

$X_{\ell ji}$ = number of red and fading trees estimated from the air in regression ℓ, substratum j, spot i,

$Y_{\ell ji}$ = number of red and fading trees in regression ℓ, substratum j, spot i,

$\bar{X}_{\ell j} = \sum_{i=1}^{n_{\ell j}} X_{\ell ji}/n_{\ell j}$ is the average number trees per spot in substratum j, regression ℓ, as estimated from the air,

and

$\bar{Y}_{\ell j} = \sum_{i=1}^{n_{\ell j}} Y_{\ell ji}/n_{\ell j}$ is the average number of trees per spot in substratum j, regression ℓ.

Then,

$$v(\hat{Y}) = \sum_{\ell=1}^{r} v(\hat{Y}_{\ell}) \tag{5}$$

where

$$\begin{aligned} v(\hat{Y}_{\ell}) = {} & N^2_{\ell} \sum_{j=1}^{s_{\ell}} (N^2_{\ell j}/N^2_{\ell})\left(1 - (n_{\ell j}/N_{\ell j})\right) \\ & \times \sum_{i=1}^{n_{\ell j}} (Y_{\ell ji} - \bar{Y}_{\ell j})^2 - 2b_{\ell} \\ & \times \sum_{i=1}^{n_{\ell j}} (Y_{\ell ji} - \bar{Y}_{\ell j})(X_{\ell ji} - \bar{X}_{\ell j}) \\ & + b^2_{\ell} \sum_{i=1}^{n_{\ell j}} (X_{\ell ji} - X_{\ell j})^2 / [n_{\ell j}(n_{\ell j} - 1)] \end{aligned} \tag{6}$$

$$\hat{Y}_h = N_{hl}(a_{\ell h} + b_{\ell h}\bar{X}_{\ell h}) + Y_{ch} \tag{7}$$

where

N_{hl} = total number of spots in the substrata of stratum h which were not 100 percent ground checked,

and

$a_{\ell h}$ and $b_{\ell h}$ are the regression coefficients for that regression ℓ in equations (3) and (4) which contain the sampled substrata of stratum h.

$$\begin{aligned} v(\hat{Y}_h) = {} & \sum_{j=1}^{s_{h\ell}} [N^2_{hj}(1 - n_{hj}/N_{hj})]/[n_{hj}(n_{hj} - 1)] \\ & \times \sum_{i=1}^{n_{hj}} \left\{(Y_{hji} - \bar{Y}_{hj}) - b_{\ell h}(X_{hji} - X_{hj})\right\}^2 \end{aligned} \tag{8}$$

where

$s_{h\ell}$ = number of substrata from stratum h included in regression,

N_{hj} = number of spots in substratum j of stratum h,

n_{hj} = number of spots ground checked in substratum j of stratum h,

Y_{hji} = number of red and fading trees on spot i, in substratum j, of stratum h,

$\bar{Y}_{hj} = \sum_{i=1}^{n_{hj}} Y_{hji}/n_{hj}$,

X_{hji} = number of red and fading trees estimated from the air on spot i, in substratum j, of stratum h,

$\bar{X}_{hj} = \sum_{i=1}^{n_{hj}} X_{hji}/n_{hj}$.

Schreuder, Hans T., William H. Clerke, Patrick J. Barry, and David M. Holland
1980. Two-stage stratified sampling with regression to assess southern pine beetle damage. USDA For. Serv., Res. Pap. SE-212, 6 p. Southeast. For. Exp. Stn., Asheville, N. C.

In a field test of two-stage stratified sampling, interpretation of aerial photos proved more reliable than sketch mapping from the air. Standard errors in estimated numbers of red, fading, and green trees and basal areas on southern pine beetle spots were reduced by using regression techniques to correlate ground and aerial observations.

KEYWORDS: Stratification, sketch mapping, aerial photographs, insect damage.

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